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NAVAL POSTGRADUATE SCHOOL

Monterey, California

ATMOSPHERIC OPTICAL TURBULENCE MEASUREMENTS
TAKEN AT
ANDERSON MESA, FLAGSTAFF, ARIZONA
BETWEEN 10-19 JULY 1990

by

G.Tirrell Vaucher, C.A. Vaucher,
and D.L. Walters

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From 10 to 19 July 1990, the Naval Postgraduate School Atmospheric Optics Group acquired atmospheric optical turbulence measurements at the 13-inch Lowell Observatory astrographic telescope dome on Anderson Mesa, 16 km southeast of Flagstaff, Arizona. This collection of transverse coherence lengths and isoplanatic angles was the last in a three-part Anderson Mesa site-survey measurement set for a large-scale, ground-based, synthetic aperture system (100-300 m baseline stellar interferometer). The intent of this report is to compile, analyze and summarize the acquired optical data, as well as correlate the meteorological and optical conditions present during the data acquisitions.

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ABSTRACT

From 10 to 19 July 1990, the Naval Postgraduate School Atmospheric Optics Group acquired atmospheric optical turbulence measurements at the 13-inch Lowell Observatory astrographic telescope dome on Anderson Mesa, 16 km southeast of Flagstaff, Arizona. This collection of transverse coherence lengths and isoplanatic angles was the last in a three-part Anderson Mesa site-survey measurement set for a large-scale, ground-based, synthetic aperture system (100-300 m baseline stellar interferometer). The intent of this report is to compile, analyze and summarize the acquired optical data, as well as correlate the meteorological and optical conditions present during the data acquisition.

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ACKNOWLEDGEMENTS

We would like to express our appreciation to the Lowell Observatory (Dr. Bob Millis - Director) for their assistance during the measurement session, and for the use of their 13" astrographic telescope dome facility on Anderson Mesa.

I. INTRODUCTION

From 10 to 19 July 1990, the Naval Postgraduate School (NPS) Atmospheric Optics Group acquired atmospheric optical turbulence measurements at the 13-inch Lowell Observatory astrographic telescope dome on Anderson Mesa, 16 km southeast of Flagstaff, Arizona. This ensemble of transverse coherence lengths (r_o) and isoplanatic angles (θ_o) is the last in a three-part Anderson Mesa site-survey measurement set for a Naval Research Laboratory (NRL) large-scale, ground-based, synthetic aperture system (100-300 m baseline stellar interferometer).

The purpose of this report is to: (1) document the NPS-July 1990 Anderson Mesa optical measurements; (2) provide a statistical analysis and summary of these optical data; and, (3) correlate the meteorological activities (using synoptic weather charts) with the optical conditions present during the experiment period. Because considerable scale-differences separate the synoptic weather phenomena (kilometers) from the optical turbulence producing events (meters), only a preliminary investigation into the third objective was undertaken.

Six appendices supplement this report:

Appendix A presents the daily synoptic weather conditions coincident with the optical data acquisition in the Anderson Mesa region.

Appendix B contains hand-edited reproductions of the National Weather Service (NWS) 850 and 300 mb synoptic weather charts for the 10-19 July period. Important meteorological features from the NWS surface maps are superimposed onto the 850 mb charts.

Appendix C displays processed r_o and θ_o data sampled between 10-19 July 1990 Universal Time Coordinated (UTC). Each night-time session is presented as a separate figure.

Appendices D and E provide nightly, un-normalized percent frequency distributions and empirical seeing quality histograms for r_o and θ_o, respectively. Specific bin intervals for the r_o and θ_o distributions, as well as intervals for the empirically derived seeing quality scales, are listed at the beginning of each Appendix.

Appendix F presents a cumulative, 1989-1990, normalized frequency distribution for both r_o and θ_o. The measurements included in these figures represent all the 1989 September, November and 1990 July processed NPS optical data sampled at both Anderson Mesa and the United States Naval Observatory, Flagstaff, Arizona.

II. EXPERIMENT OVERVIEW

Various portions of Chapter II were taken from the Atmospheric Optical Turbulence Measurements Taken At Anderson Mesa, Flagstaff, Arizona Between 13-19 November 1989 report (Vaucher, Vaucher, and Walters, 1991). For additional background information, the reader is encouraged to review Vaucher, Vaucher, and Walters (1990).

A. SITE TOPOGRAPHY

Anderson Mesa is an 125 m high plateau situated in the ponderosa pine and lake mesa-country 16 km southeast of Flagstaff and 18 km west of the high desert floor. The 13-inch astrographic telescope dome used for optical data gathering is approximately 2.2 km above sea level and located near the southwest edge of the mesa (slightly south of the 31-inch dome). Figure 1 displays a 3-dimensional topographical view of Anderson Mesa, showing the location of the Lowell Sites, as well as major features of interest. The contour interval is 5 meters.

B. DATA ACQUISITION

All data acquisition sessions commenced at local sunset and concluded with the onset of local sunrise twilight. The total measurement period was 9-10 hours per night. Due to the onset of the northern Arizona, July-August monsoon activity (thunderstorms and multi-layered clouds), actual sampling began around 2300 Mountain Standard Time (MST) and continued on to local sunrise. Occasionally, the local weather activity would permit data collection earlier in the evening, but such sampling was very limited.

1. Optical Instrumentation and Measurements

The optical turbulence parameters gathered throughout the experiment included the isoplanatic angle (θ_o) and the transverse coherence length (r_o). A brief description of these parameters is available in Vaucher (1989). The isoplanometer and transverse coherence length sensors were designed and built by Dr. D.L. Walters. Stevens (1985) and Walters, Favier, and Hines (1979), respectively, describe specific details for each instrument. Vaucher, Vaucher and Walters (1990) explain the optical systems, configurations, and data acquisition procedures utilized during the Anderson Mesa site survey missions.

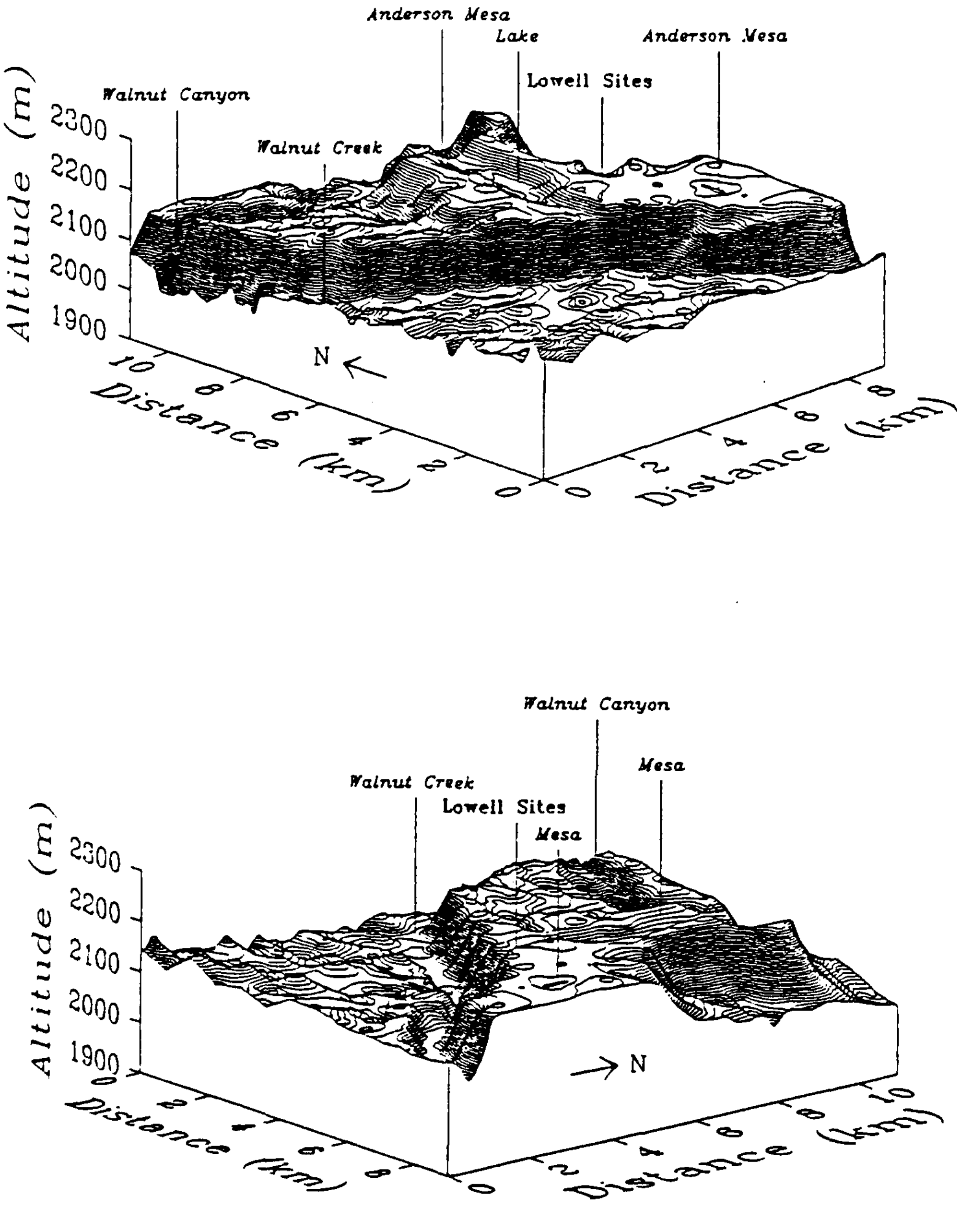


Fig 1. Topographical Views of the Lowell Sites, Anderson Mesa, Arizona

All optical measurements were recorded in Universal Time Coordinated (UTC). The conversion from local Mountain Standard Time (MST) to UTC is:

$$\text{Time(UTC)} = \text{Time(MST)} + 7 \text{ hours}.$$

Arizona retains MST throughout the year.

2. Synoptic Weather Information

GOES-WEST Visible Satellite Images, as well as surface, 500 mb, and 200 mb NWS charts provided an on-site evaluation of the synoptic weather conditions. These also helped to detect potential sources of optical turbulence during the experiment session.

Post-experiment analysis of synoptic weather activity around Flagstaff was based on the six NWS standard isobaric charts. These constant pressure surfaces and their equivalent heights are:

Pressure (mb)	Equivalent Height Above Sea Level (km)
Surface	0.1
850	1.4
700	3.0
500	5.5
300	9.2
200	12.0

It should be noted that the equivalent heights defined above represent averaged values. For any given pressure level, the actual height will vary as Low and High pressure systems traverse the site (Vaucher, Vaucher, and Walters, 1990). Appendix B provides two of the six NWS isobaric surfaces (850 and 300 mb) used in post-analysis.

III. DATA ANALYSIS

A. OPTICAL DATA ANALYSIS

1. Transverse Coherence Length Data, r_o

Figure 2 displays the nightly r_o averages and standard deviations for 10-19 July 1990. Using the Empirical Seeing Quality Scale described in Appendix D, the initial five r_o sampling sessions indicate the dominant optical conditions to be "mediocre" (51-100 mm). The seeing quality of the remaining two nights is "good" (101-200 mm). Table 1 lists the individual r_o nightly averages and standard deviations plotted in Figure 2, as well as the standard deviation of the mean and number of data points collected during each session.

Figure 3 presents the normalized r_o frequency distribution for each session. July 10, 12 and 15 peak at 80-90 mm. On 13 July, the peak frequency is between 100-110 mm. For this same session, 76% of the values qualify as "mediocre", while only 24% of the measurements connote "good" to "excellent" optical conditions (Table 3). High r_o numbers occur on 18-19 July. Peak values are 100-110 mm and 90-100 mm, respectively. The dominant empirical seeing conditions for these last two nights are both "good" (Table 3).

Consolidating all 1,501 r_o samples acquired between 10-19 July, the cumulative normalized r_o frequency distribution maximum (Figure 4) has a wide maximum between 80-110 mm, with a small peak between 80-90 mm. This implies that the average seeing over the 10-day period hovered around one arc-second. Examining the individual r_o points, "mediocre" conditions dominate with 909 samples (61%) registering between 51-100 mm, while 557 values (37%) identify "good" to "very good" optical conditions. The overall trend of the oscillating 10 to 19 July average r_o pattern suggests that optical conditions were improving.

TABLE 1. TRANSVERSE COHERENCE LENGTH STATISTICS

Date (UTC)	Number of Data Points	Average r_o (mm)	Standard Deviation (mm)	Standard Deviation of Mean (mm)
10 July	33	72.5	10.4	1.8
12 July	117	83.7	24.5	2.3
13 July	241	92.9	17.1	1.1
15 July	286	74.0	10.3	0.6
17 July	40	50.1	7.3	1.2
18 July	373	114.6	28.7	1.5
19 July	411	108.5	29.9	1.5

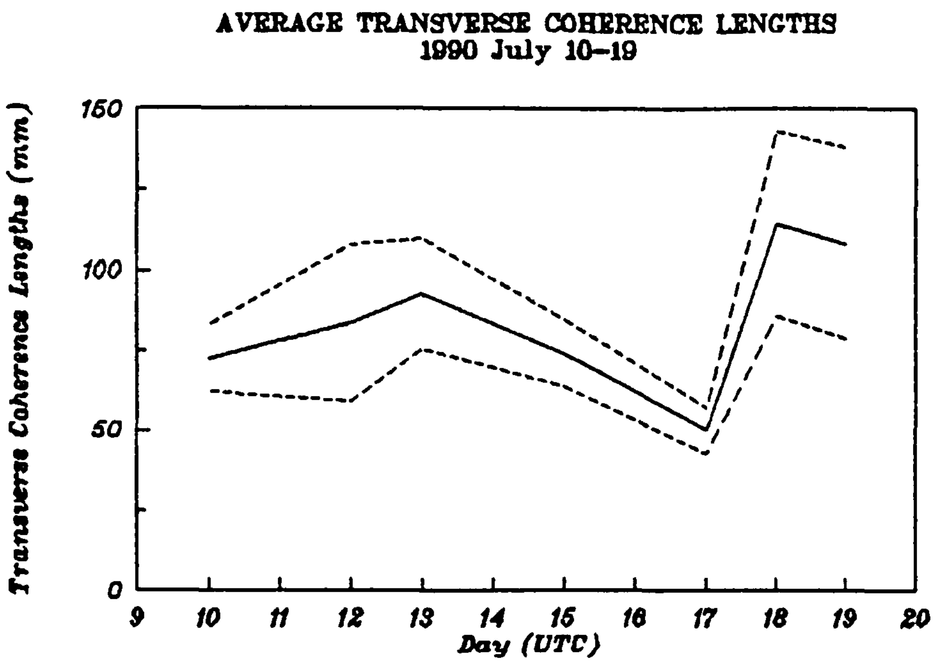


Fig 2. **Average Transverse Coherence Lengths (90 July 10-19)** Solid line is data average; Dashed line is standard deviation of the data.

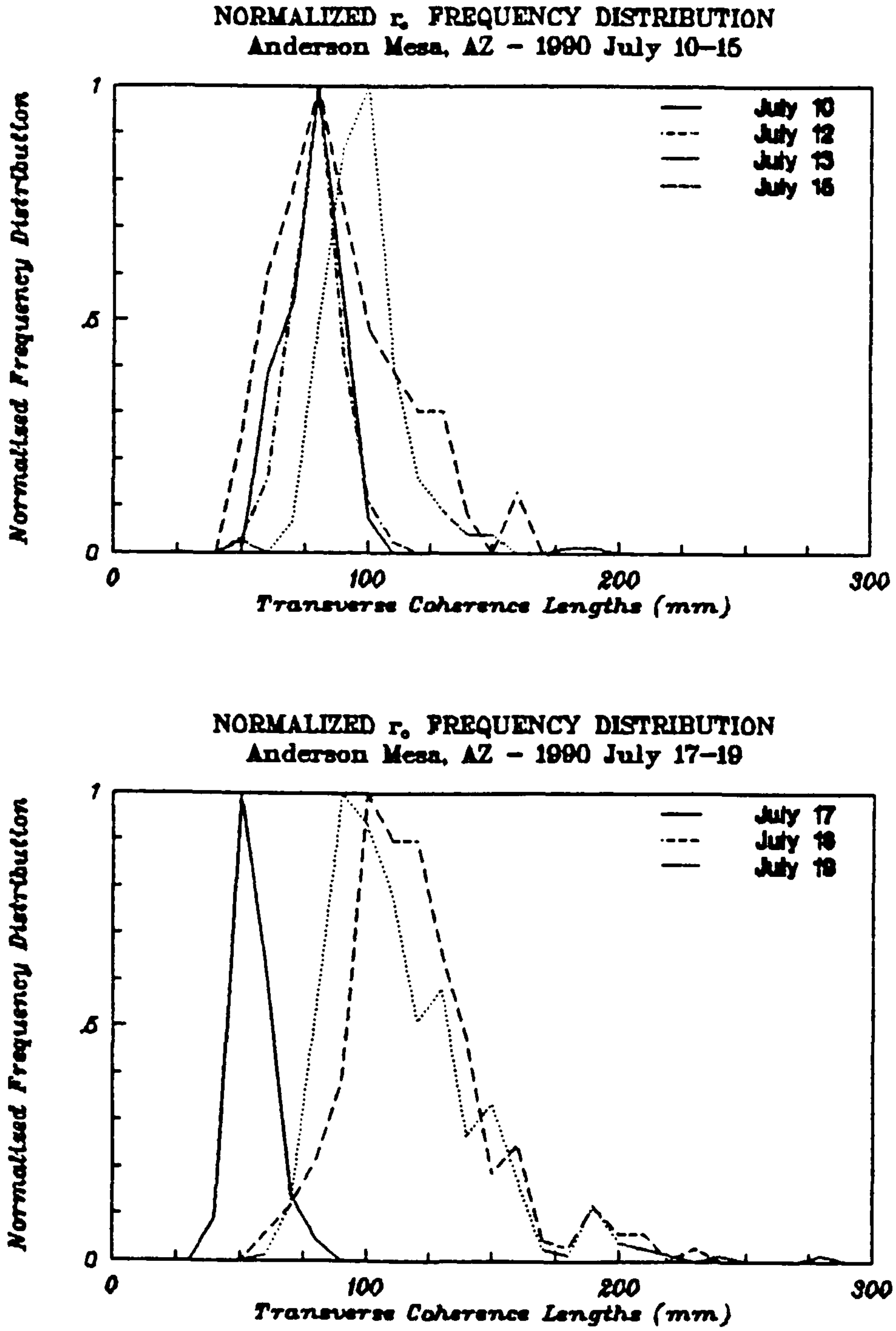


Fig 3. Normalized r_o Frequency Distributions for Anderson Mesa, Az (90 July 10-19).

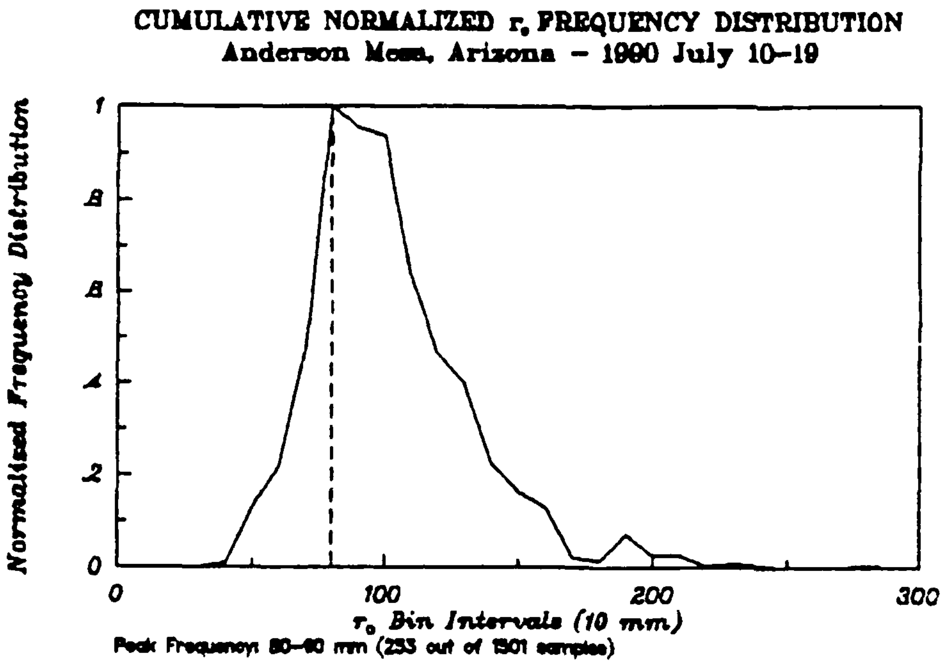


Fig 4. Cumulative Normalized r_o Frequency Distribution for the Anderson Mesa 1990 July 10-19 session.

2. Isoplanatic Angles Data, θ_o

Figure 5 displays a gradual increase in the nightly average θ_o between 13 and 19 July (hardware problems precluded θ_o data acquisition prior to 13 July). Table 2 tabulates the number of θ_o samples collected per night, as well as the nightly average, standard deviation, and standard deviation of the mean. Note: Hardware problems with the θ_o sensor prohibited measurements prior to 13 July. Also, due to a cirrus and residual cumulus cloud cover, 17 July contains only two samples. It follows that any statistics pertaining to 17 July are unreliable.

Figure 6 shows the normalized θ_o frequency distributions for each night. Examining the peak frequencies, the most commonly acquired values are initially between 8-9 urad (13 July). By 19 July, θ_o peak frequencies have gradually increased to 11-12 urad.

Compiling all 3,454 13-19 July samples, the cumulative normalized θ_o frequency distribution (Figure 7) has a primary maximum between 9-10 urad. The dominant cumulative empirical seeing quality is "mediocre" (52% of the entire data set). Despite the improving optical conditions, only 14% of the total measurements qualify as "good" (12-20 urad).

TABLE 2. ISOPLANATIC ANGLE STATISTICS

Date (UTC)	Number of Data Points	Average θ_o (urad)	Standard Deviation (urad)	Standard Deviation of Mean (urad)
13 July	396	7.48	1.90	0.10
15 July	730	6.45	1.04	0.04
17 July	2	11.54	1.87	1.3
18 July	1317	10.00	1.93	0.05
19 July	1009	10.70	2.31	0.07

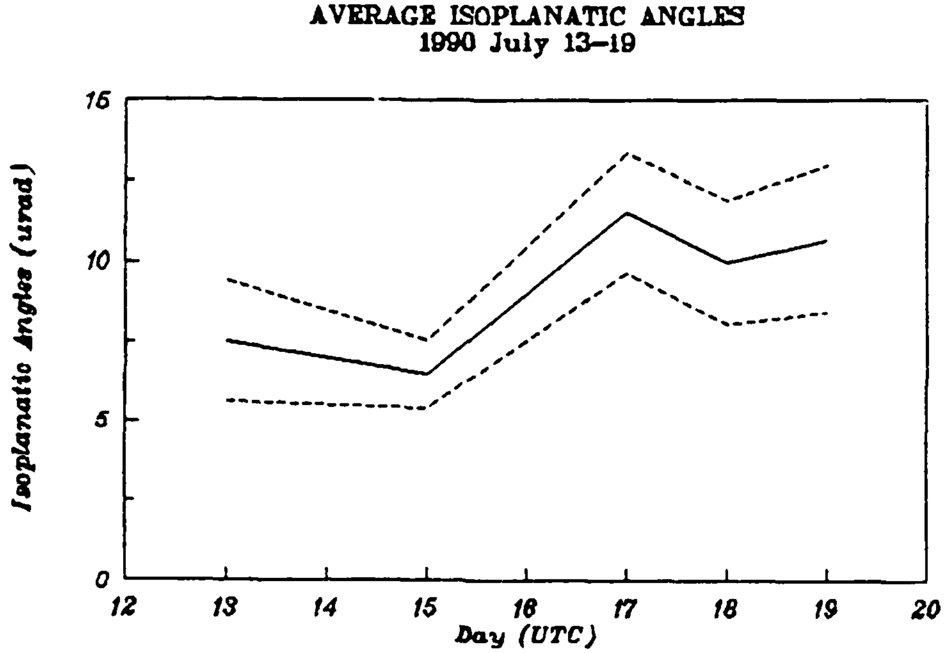
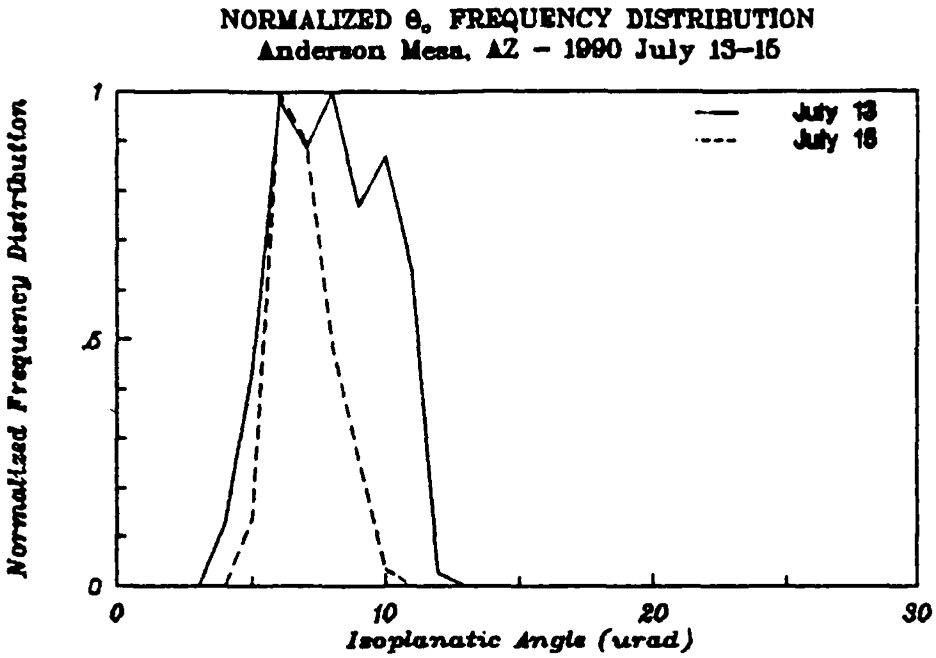


Fig 5. **Average Isoplanatic Angles (90 July 13-19)** - Solid line is data average; Dashed line is standard deviation of the data.



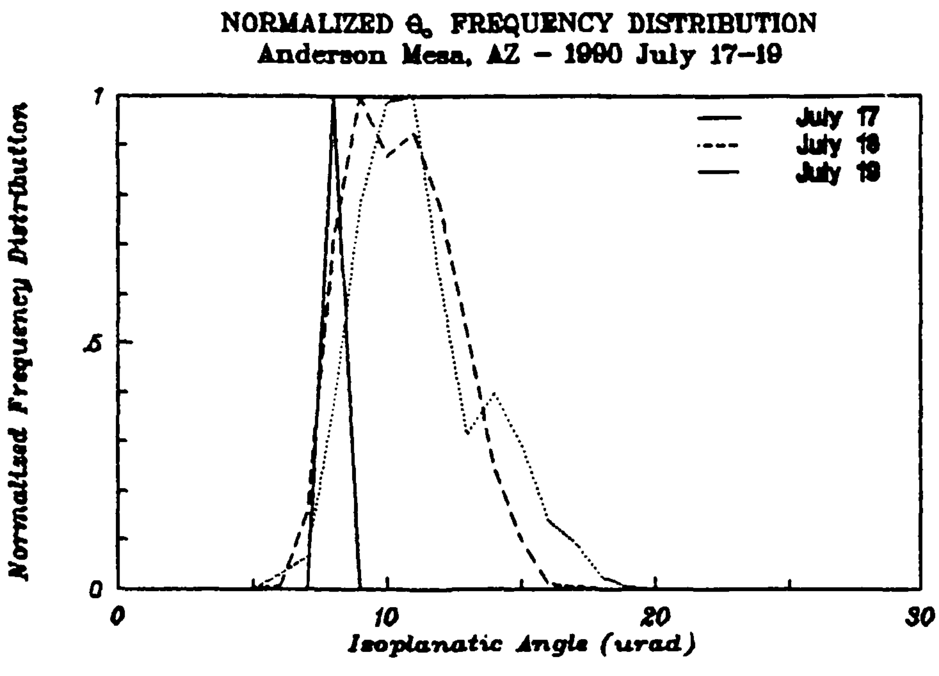


Fig 6. Normalized Θ_o Frequency Distributions for Anderson Mesa, Az (90 July 13-19).

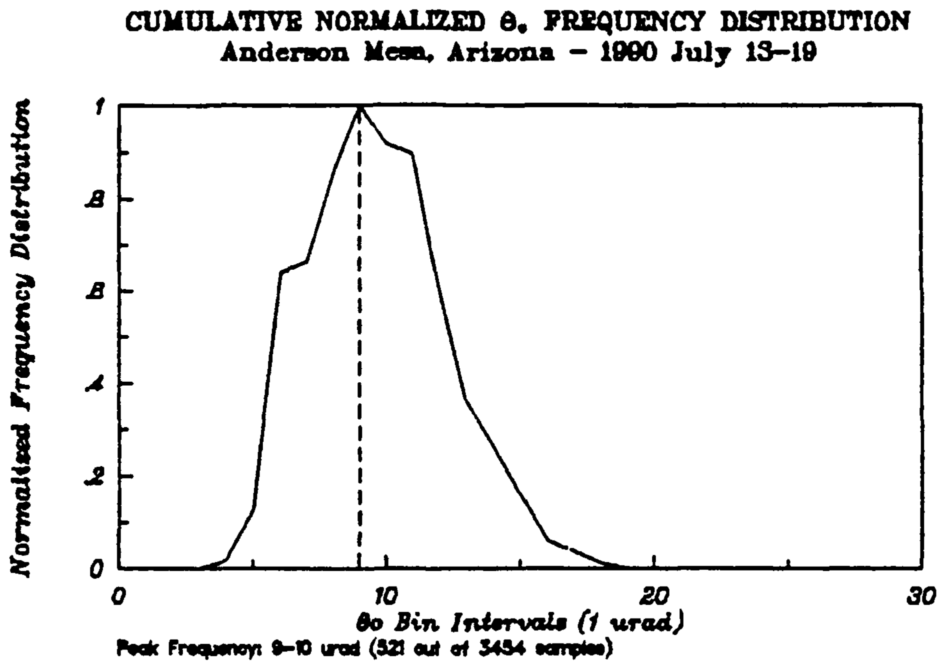


Fig 7. Cumulative Normalized θ_0 Frequency Distribution for the Anderson Mesa 1990 July 13-19 session.

B. METEOROLOGICAL REVIEW

1. General Synoptic Weather

Typical July-August monsoon activity dominated the northern Arizona weather pattern throughout the sampling session. The general synoptic weather scenario for this period included: a persistent thermal Low over the southwestern states; a mid-level High (ridge) extending from the central California coast to Texas, Canada to Mexico; and, no jet stream activity aloft over Arizona. Hurricane Bostow and later, Tropical Storm Genevieve (both off of Baja, California), assisted the daily build-up of thunderstorm activity by pumping moisture over Arizona.

2. Site Weather Summary

The major obstacle for this monsoon season experiment was the frequent occurrence of a multi-layer cloud cover. This optical handicap was a by-product from the daily build-up and nightly dissipation of large anvil cumulonimbus. In general, the observing session was productive between 2300/2400 MST to sunrise. Measurements were occasionally acquired earlier in the evening, but such sampling was often short-lived. For some nights, the cloud cover persisted until dawn (e.g., 11 July).

On 19 July 1990, the following observation was entered into the logbook. While a local severe thunderstorm persisted near Anderson Mesa (just outside of the thunder's audible range, between 8-16 kilometers away), optical sampling revealed r_o values between 100-250 mm. The θ_o sampling (slightly delayed due to the intensity and frequency of the lightning) displayed 7-13 urad. The implication of such high numbers is two-fold: first, the effective range of thunderstorm induced optical turbulence activity around the cumulonimbus anvil is apparently quite limited; and second, "good" (100-200 mm) to "very good" (201-300 mm) seeing conditions are possible even during the Arizona monsoon period.

For a day by day review of the synoptic weather activity, see Section IV (Data Summary) and Appendix A. Appendix B provides hand-edited 850 and 300 mb NWS charts for additional reference.

IV. DATA SUMMARY

A. CONSOLIDATING THE PARAMETERS

Table 3 consolidates informative optical and meteorological parameters acquired between 10-19 July 1990. While the mean r_o and θ_o values (Parts A and B) appear earlier, the "Empirical:" columns are seen for the first time. The "Empirical: Dominant Conditions" columns are calibrated by the Empirical Seeing Quality Scales (Appendices D and E) and provide a quick interpretation of typical r_o and θ_o numbers for each night. The "Empirical: % >= 'Good'" columns, also standardized by the Empirical Seeing Quality Scales, indicate the total percent of individual datum points per session qualifying as "good" to "excellent" (101-500 mm).

TABLE 3. OPTICAL/METEOROLOGICAL SUMMARY - ANDERSON MESA, AZ

A. Transverse Coherence Length:				B. Isoplanatic Angle:		
July Date (UTC)	Mean Value (mm)	Empirical: Dominant Conditions	Empirical: % >= "Good"	Mean Value (urad)	Empirical: Dominant Conditions	Empirical: % >= "Good"
10	72.5	Mediocre(100%)	0			
12	83.7	Mediocre(71%)	24			
13	92.9	Mediocre(76%)	24	7.48	Poor(58%)	0
15	74.0	Mediocre(98%)	1	6.45	Poor(89%)	0
17	50.1	Poor(58%)	0	11.54	Medio/Good(50%)	50
18	114.6	Good(66%)	68	10.00	Mediocre(67%)	17
19	108.5	Good(52%)	53	10.70	Mediocre(66%)	25

C. Synoptic Meteorological Conditions:

July Date (UTC)	Maximum Wind Gradient Horizontal Wind Shear (at 200 mb) ($\times 10^{-5}$) s^{-1}	Frontal(F)/ Non-Frontal(NF)/ Transitional(T)
10	3.6	NF
11	2.3	NF
12	1.2	F
13	3.5	F
15	3.1	T
17	1.2	NF
18	1.7	NF
19	2.1	NF

Turbulence aloft has been loosely associated with the presence of a 200 or 300 mb jet stream flow (70 kt or greater wind maximum). To calibrate the jet stream activity, the 200 mb NWS synoptic weather chart isotaches were used to calculate the maximum horizontal wind speed shear (wind gradient) over the site. The results are tabulated in Part C of Table 3.

The second column in the meteorological parameters section (Part C), "Frontal/Non-Frontal/Transitional", aids in interpreting the potential optical quality for the specified 24 hour UTC period. Generally, Frontal weather produces turbulence with poor seeing conditions. Non-Frontal weather renders a stable atmosphere of generally high optical quality. Transitional implies a changeover from either Frontal or Non-Frontal conditions, and often indicates an atmosphere in which separate cold and warm air masses collide and mix, frequently producing very turbulent layers and subsequently poor optical seeing. For further information, consult Vaucher, Vaucher, and Walters (1990).

B. OPTICAL/METEOROLOGICAL DATA CORRELATIONS

1. Daily Optical/Meteorological Activity

The following discussion assimilates the various important optical and meteorological parameters outlined in the Data Analysis Section (Part III) and Appendices A through E. Table 3 should be consulted throughout.

The major meteorological challenge for this optical experiment was the frequent night-time, multi-layer cloud cover. In general, the early evening data acquisition sessions were postponed 3-6 hours due to rain and/or cloud obstruction. Both phenomena were characteristic of the daily thunderstorm build-up and nightly dissipation (a typical northern Arizona July-August monsoon season cycle).

a. 10-12 July 1990

From 10 - 12 July 1990, monsoon weather conditions dominated over most of Arizona, New Mexico, and northern Mexico. Specifically, early morning cumulus development rapidly evolved into afternoon cumulonimbus. By evening, multi-layer cloud cover and heavy rain showers severely restricted the observations. Hurricane Bostow (off of Baja) propagated this daily monsoon cycle by pumping moisture over Arizona. Sampling between clouds, the a erage

r_o for 10 and 12 July was 72 mm and 84 mm, respectively. Extensive cloud cover prohibited any 11 July optical measurements.

Synoptic weather structure for 10 - 12 July included a surface thermal Low over southwestern Arizona and Mexico. From 850-500 mb, the atmospheric structure was initially unclear. By 12 July, a High pressure (850-200 mb) system had emerged, stretching over the western states from Canada to Arizona. Aloft (200-300 mb), High pressure hovered over New Mexico and Arizona, with southwesterly winds ranging from 5-30 knots (kt). No jet stream activity was present over Arizona.

b. 13 July 1990

By 13 July, a θ_o sensor hardware problem had been fixed. Despite persistent cloud cover, three hours of data were acquired. Initial r_o measurements averaged around 120 mm, then gradually decayed to 90 mm. The nightly average r_o measurement was 93 mm. Isoplanatic angle values showed an increasing trend from 6 to 9 urad over the observing period. The nightly average θ_o was 7.5 urad.

Flagstaff regional weather conditions for 13 July continued to be dictated by the monsoon activity. The synoptic weather pattern for the surface layer included a thermal Low over California, Arizona, and northern Mexico; and, the tail-end of a cold front swinging through eastern/ southeastern Arizona. From 700-200 mb, a High dominated the western states extending from Canada to Mexico. The closest upper level jet (northwesterly, 70 kt) was over eastern Colorado at 200 mb.

c. 14-16 July 1990

On 14 and 16 July, monsoon rains prohibited any optical data collection. The 15 July sampling session, however, acquired 2.5 hours of measurements, despite the daily thunderstorm build-up. The average r_o for 15 July was 74 mm ("mediocre" conditions). θ_o values commenced around 8 urad, dipped to 5 urad, then finally increased to 7 urad. The average θ_o for the predominantly "poor" seeing conditions was 6.4 urad.

The synoptic weather structure for 14 - 16 July remained consistent with previous days: a thermal surface Low over the southwestern states; and, between 700-200 mb, a High/ridge hovered over the western states, extending from Washington to New Mexico. The jet closest to the site was a northwesterly 70 kt jet (15 July: 200 mb) over the Texas panhandle/eastern New Mexico region. By 16 July, the only noted jet stream was well to the north along the USA/Canadian boarder.

d. 17 July 1990

Based on a very small sampling set (40 points), the average r_o for 17 July was 50 mm. Isoplanatic angles averaged 11.5 urad. Over Arizona, rainstorms and thunderstorms evolved throughout the day. The synoptic weather structures included a surface thermal Low over southwestern Arizona; a surface High in northeastern Arizona; and, Tropical Storm Genevieve off the Baja coastline. Mid-layer weather charts (850-500 mb) displayed no clearly defined structure over the southwestern states. A quasi-ridge system aloft (300-200 mb) extended from Oregon to Louisiana.

e. 18 July 1990

Dominant optical conditions for 18 July were "good". Over four hours of nearly continuous sampling revealed an average r_o of 115 mm (less than one arc-second). The session's observing began with r_o values around 80 mm. These quickly increased to 120 mm, where they continued for 2-3 hours. The r_o numbers increased again to 130 mm for 30 minutes, then finally dropped to 100 mm by the end of the run. Isoplanatic angles commenced with values around 8 urad, then gradually increased to 13 urad. The average nightly θ_o was 10 urad.

Monsoon weather conditions dominated the Flagstaff area throughout the 18 July daylight hours. By evening, the influence of the surface High over northeastern Arizona/Nevada helped to dry the atmosphere. The synoptic surface pattern continued with: a thermal Low over southwestern Arizona; a High over northeastern Arizona and Nevada; and, Tropical Storm Genevieve off Baja. Mid-level charts presented no clearly defined structures over the site. Aloft (200-300 mb), a High presided over Arizona. No 200-300 mb jet stream activity was evident.

f. 19 July 1990

The final observing session, 19 July, continued to display improved optical conditions. Despite the daily thunderstorm build-up and dissipation (monsoon activity), four hours of measurements were acquired. The initial r_o sampling hovered around 100 mm. These values quickly increased to 125 mm, before very gradually decreasing to 90 mm. Isoplanatic angles began around 10 urad. After two hours, θ_o increased to 15 urad, then tapered-off to 14 urad. Average r_o and θ_o values were 108 mm and 11 urad, respectively.

In keeping with the weather pattern of previous days, a daytime thermal Low developed over southwestern Arizona on 19 July. A surface High over northeastern Arizona helped dry the atmosphere by evening. The now Tropical Depression Genevieve continued to decay off the coast of Baja. From 700-200 mb, a High/ridge dominated over Arizona. No 200-300 mb jet was present over Arizona.

An interesting observation (also mentioned in Chapter III) was recorded in the logbook for 19 July 1990. While a local severe thunderstorm persisted near Anderson Mesa (just outside of the thunder's audible range, 8 to 16 kilometers away), optical sampling revealed r_o measurements between 100 and 250 mm. The θ_o sampling (slightly delayed due to the intensity and frequency of the lightning) displayed 7-13 urad. The implication of such high numbers is two-fold: first, the effective range of thunderstorm-induced optical turbulence activity around the cumulonimbus anvil is apparently quite limited; second, "good" (r_o: 100-200 mm, θ_o: 12-20 urad) and "very good" (r_o: 201-300 mm) optical seeing conditions are possible, even with thunderstorm activity in the area. This may be attributed to the subsidence (downdraft) surrounding the convective column of the cumulonimbus.

2. Wind Shear vs. Dominant Optical Conditions

A cross comparison of the horizontal wind shears at 200 mb and the empirical-dominant conditions columns in Table 3 provides limited correlations. For the first five experiment days, the relatively large horizontal wind shears (average = 3 s^{-1}) are coincident with "poor" to "mediocre" optical conditions. The last three days of horizontal wind gradient data (average = 2 s^{-1}) imply slightly better optical conditions. Empirically, the dominant conditions of

"mediocre" to "good" do loosely compliment such an assessment. The θ_o data has a higher correlation to the 200 mb horizontal wind shear than r_o . This is somewhat expected, since θ_o is inherently more sensitive to turbulence aloft.

V. CONCLUSIONS/RECOMMENDATIONS

The primary purpose of this study was to evaluate the Flagstaff, Arizona region as a potential site for a large baseline stellar interferometer. The initial measurement sessions, completed in September and November 1989 by the Atmospheric Optics Group (NPS), found mixed results. The September survey found that "despite the constant colliding of cold and warm air masses typical for this area in September, significant 'good' to 'excellent' seeing conditions occurred" (Vaucher, Vaucher, Walters, 1990). In contrast, the November survey yielded only limited "good" quality optical data. "The fragmented layers of contrasting air masses (a predominantly transitional weather pattern), coupled with an accelerated circulation (jet) over the site (300-200 mb), rendered an almost continuously turbulent optical environment". (Vaucher, Vaucher, Walters, 1991)

The July 1990 measurement session observed optical conditions during the northern Arizona summer monsoon season. Expecting the very dynamic (monsoon-driven) atmosphere to dictate only "mediocre" seeing quality, the authors were surprised to find optical conditions greater than or equal to "good" over several nights (18-19 July). This may be related to the discovery that "good" (101-200 mm, 12-20 urad) and "very good" (201-300 mm) atmospheric optical measurements are possible even within a close proximity to an active and audible thunderstorm complex (19 July).

In summary, each of the three experiments represent a snapshot of the "normal" atmospheric conditions over Anderson Mesa. Further seasonal measurements, supplemented with a climatological study of the thermodynamic and shear producing events, would help to resolve the question concerning the frequency of "good" to "excellent" seeing under less than ideal weather patterns. Based on the limited optical data collected from all three sessions (Appendix F), the authors tentatively recommend the Flagstaff region be considered as a potential site for a large baseline stellar interferometer.

APPENDIX A. DAILY SYNOPTIC WEATHER SUMMARY

Site: Anderson Mesa, Flagstaff, Arizona
Time Period: 10-19 July 1990 UTC
Equipment Used: Transverse Coherence Length Sensor
Isoplanatic Angle Sensor
National Weather Service Synoptic Charts

Monsoon activity dominated the weather conditions throughout the sampling session. Despite the daily build-up of thunderstorms, average transverse coherence lengths (r_o) for this site ranged from approximately 80 to 250 mm. Average isoplanatic angles (θ_o) spanned 6-15 urad. The general synoptic weather scenario for this session included: a thermal Low over the southwestern states; a mid-level High/ridge extending from the central California coast to Texas, Canada to Mexico; and, no jet stream activity aloft over Arizona. Hurricane Bostow and later, Tropical Storm Genevieve (both off of Baja, California), assisted the daily build-up of thunderstorm activity by pumping moisture over Arizona.

Logbook notes:

During this monsoon season experiment, the major obstacle for sampling was the frequent night-time, multi-layer cloud cover. In general, the actual data acquisition began around 2300 MST and continued on to local sunrise. Occasionally, the patient observer would wring out some measurements earlier in the evening, but such sampling was often very limited.

19 July 1990: While a local severe thunderstorm persisted near Anderson Mesa (just outside of the thunder's audible range, between 8-16 kilometers away), optical sampling revealed r_o values of 100-250 mm. The θ_o sampling (slightly delayed due to the intensity and frequency of the lightning) displayed 7-13 urad. The implication is two-fold: first, though thunderstorm activity is known as a source of turbulence, the effective range of the optical turbulence is apparently limited; and second, "good" (100-200 mm) to "very good" (201-300 mm) seeing conditions are possible even during the Arizona monsoon season.

DAY BY DAY SYNOPTIC WEATHER SUMMARY

ANDERSON MESA, FLAGSTAFF, ARIZONA (1990)

Dates: 09 July, 2300 hrs - 19 July, 0200 hrs (MST)
10 July, 0600 hrs - 19 July, 0900 hrs (UTC)

10 July 1990: Monsoon conditions prevail over most of Arizona/New Mexico/northern Mexico. Multi-layer cloud cover and heavy rain showers over the site permit only a brief sampling interval. Surface synoptic conditions include: a High over Utah; a Pacific High off of Oregon; and, a thermal Low over Baja/New Mexico. No distinct mid-layer (850-500 mb) structure dominates over the western continental states. Aloft (200-300 mb), High pressure hovers over New Mexico/ Arizona, southwesterly winds dominate over the California/ Montana/New Mexico region. Over the Arizona site, winds (200-300 mb) are southwesterly at 15-30 knots (kt).

11 July 1990: Hurricane Bostow (off of Baja, California) continues to fuel the Monsoons by pumping moisture over Arizona. Surface synoptic conditions include: a Low over Idaho/Oregon; and, a thermal Low over southwestern Arizona/ Mexico. From 850-500 mb, the atmospheric structure is not well-defined. Aloft (200-300 mb), southwesterly 5-15 kt winds traverse the site. An upper level High extends from southern California to Virginia, and Canada to Mexico. No 200-300 mb jet stream activity is present over Arizona. Due to the extensive cloud cover over the site, no measurements could be sampled.

12 July 1990: In typical monsoon fashion, the early morning cumulus develops into afternoon cumulonimbus. By evening, the cloud cover severely restricts the observations. Synoptic conditions include: a surface Low over Mexico; and, a surface ridge over California through New Mexico. High pressure (850-200 mb) stretches over the western states extending from Canada to Arizona. No 200-300 mb jet is over Arizona.

13 July 1990: Monsoon conditions (thunderstorm activity) persist over the Flagstaff region. The synoptic weather configuration for the surface layer includes: a thermal Low over California/Arizona/northern Mexico; a great basin High (over Nevada) that evolves into a Low between 0000 and 1200 UTC; and, the tail-end of a cold front swinging through eastern/southeastern Arizona. The 850 mb structure includes a Low over Arizona expanding to Utah. From 700-200 mb, a High dominates the western states extending from Canada to Mexico. The closest jet (northwesterly, 70 kt) is over eastern Colorado at 200 mb.

14 July 1990: Monsoon rains prohibit data collection. The limited synoptic charts (850, 500, 300 mb) available describe a High/ridge over the western states from southern Canada to New Mexico. The local Flagstaff TV news displayed weather maps with a thermal Low over the southwestern states, and a Low over Mid/Northern California.

15 July 1990: In addition to the daily thunderstorm build-up, the synoptic structure remains consistent with previous days: a thermal surface Low over southwestern states, a surface High over Nevada; between 700-200 mb, a High/ridge hovers over the western states extending from Washington to New Mexico. The 1200 UTC 300 mb NWS chart shows a shortwave over Nevada/Utah. The jet closest to the site is a northwesterly 70 kt jet (200 mb) over the Texas panhandle/ eastern New Mexico region.

16 July 1990: No synoptic charts were available for post-experiment analysis. Local cloud cover prohibited any optical data acquisition. Personal log observations reports thick clouds all day over Flagstaff. A brief window of stars appear over the site around local midnight, however, the exposed stars were not the correct magnitude for sampling. The local TV news displayed weather maps with: a thermal Low over Arizona/California; a Low over northern California; a High over Montana/Idaho/Wyoming; and, the jet stream well to the north along the Canadian/USA boarder.

17 July 1990: Over Arizona, rainstorms and thunderstorms evolve throughout the day. The synoptic weather structures include: a surface thermal Low over southwestern Arizona; a surface High in northeastern Arizona; and, Tropical Storm Genevieve off the Baja coastline. Mid-layer weather charts (850-500 mb) display no clearly defined configuration over the southwestern states. A quasi-ridge system aloft (300-200 mb) extends from Oregon to Louisiana.

18 July 1990: Monsoon weather conditions still dominate the Flagstaff area throughout the day. By evening, the influence of the surface High over northeastern Arizona/ Nevada helps to dry the atmosphere. The synoptic surface pattern continues with: a thermal Low over southwestern Arizona; a High over northeastern Arizona and Nevada; and, Tropical Storm Genevieve off Baja. Mid-level charts present no clearly defined structures over the site. Aloft (200-300 mb), a High exists over Arizona, extending from Idaho to Texas. No 200-300 mb jet is evident.

19 July 1990: In addition to the local thunderstorm build-up during the day (monsoon activity), the synoptic activity is consist with previous days: a thermal Low is over southwestern Arizona; a surface High over northeastern Arizona helps to dry the atmosphere by evening; and, the now Tropical Depression Genevieve continues to decay off the coast of Baja. From 700-200 mb, a High/ridge dominates over Arizona. This structure extends from California to Colorado to Texas. No 200-300 mb jet is present over Arizona.

APPENDIX B. NWS 850 AND 300 MB SYNOPTIC WEATHER CHARTS

The following National Weather Service (NWS) 850 and 300 mb isobaric weather charts display the synoptic activity present during the 10-19 July 1990 UTC optical measurement session. As indicated in the text, 14 and 16 July 1990 NWS charts were unavailable for this analysis.

A plus symbol identifies the location of the Anderson Mesa (Flagstaff, AZ) data collection site. Surface fronts (solid lines) and troughs (dashed lines), as well as surface High and Low pressure systems (circled "H" and "L" labels) have been superimposed onto the 850 mb charts. Dashed lines on the 200 mb charts trace the jet stream activity. Specifically, these dashed lines outline the 70 kt isotaches, as well as the labelled jet streak maxima (generally, 110 kt or greater).

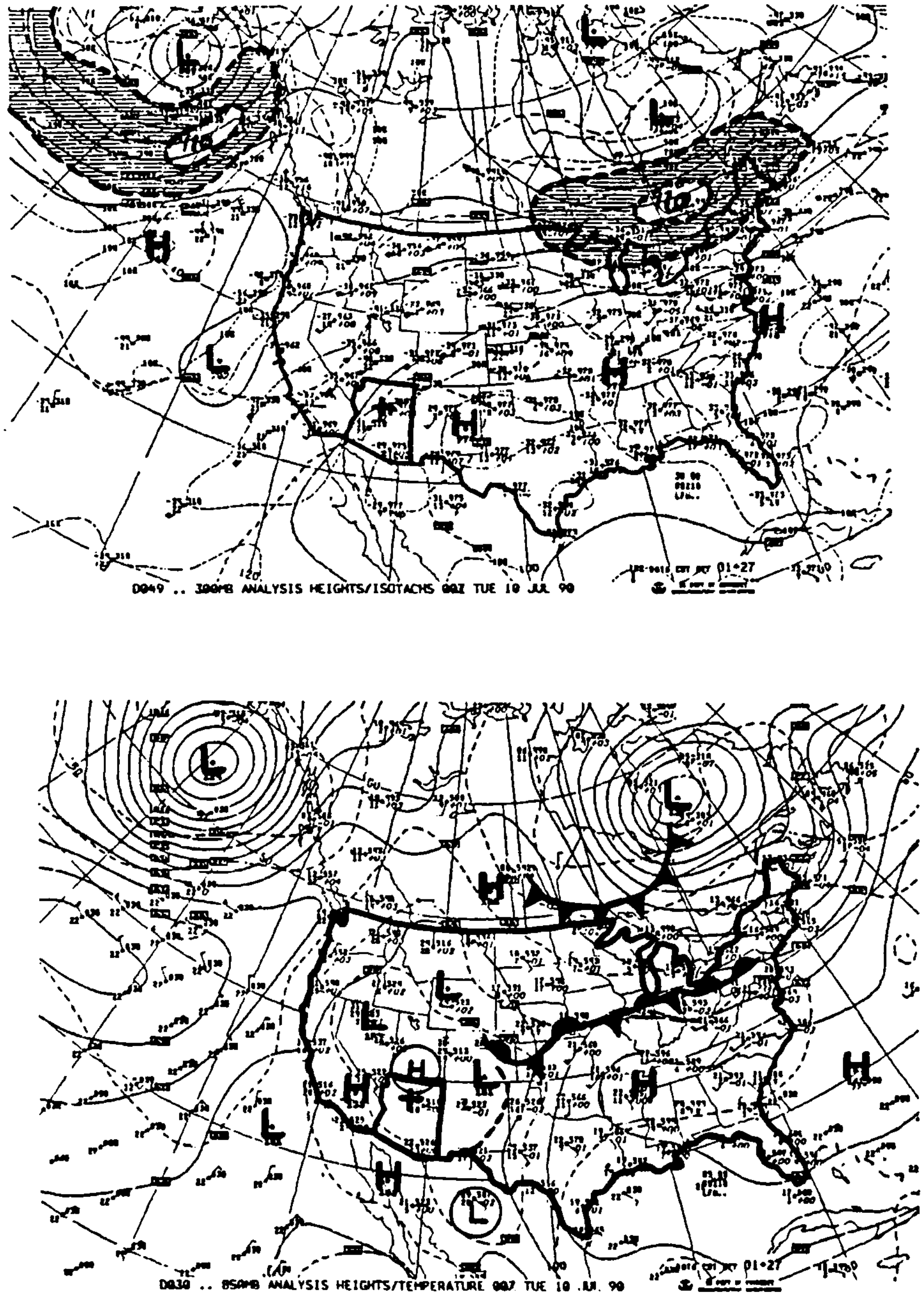


Fig 8. **NWS 850** (bottom) **and 300** (top) **mb Charts: July 10, 0000 UTC**

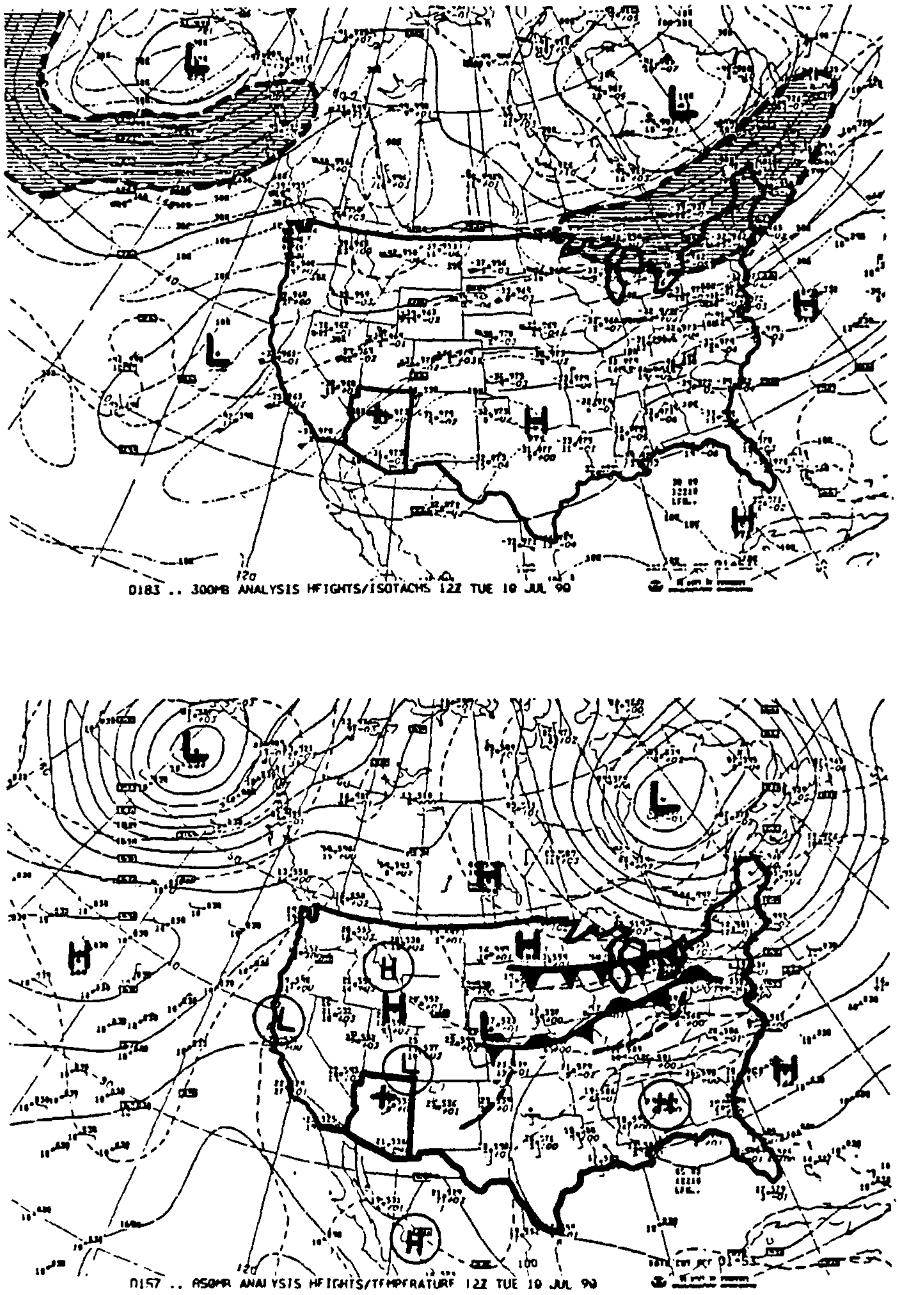


Fig 9. NWS 850 (bottom) and 300 (top) mb Charts: July 10, 1200 UTC

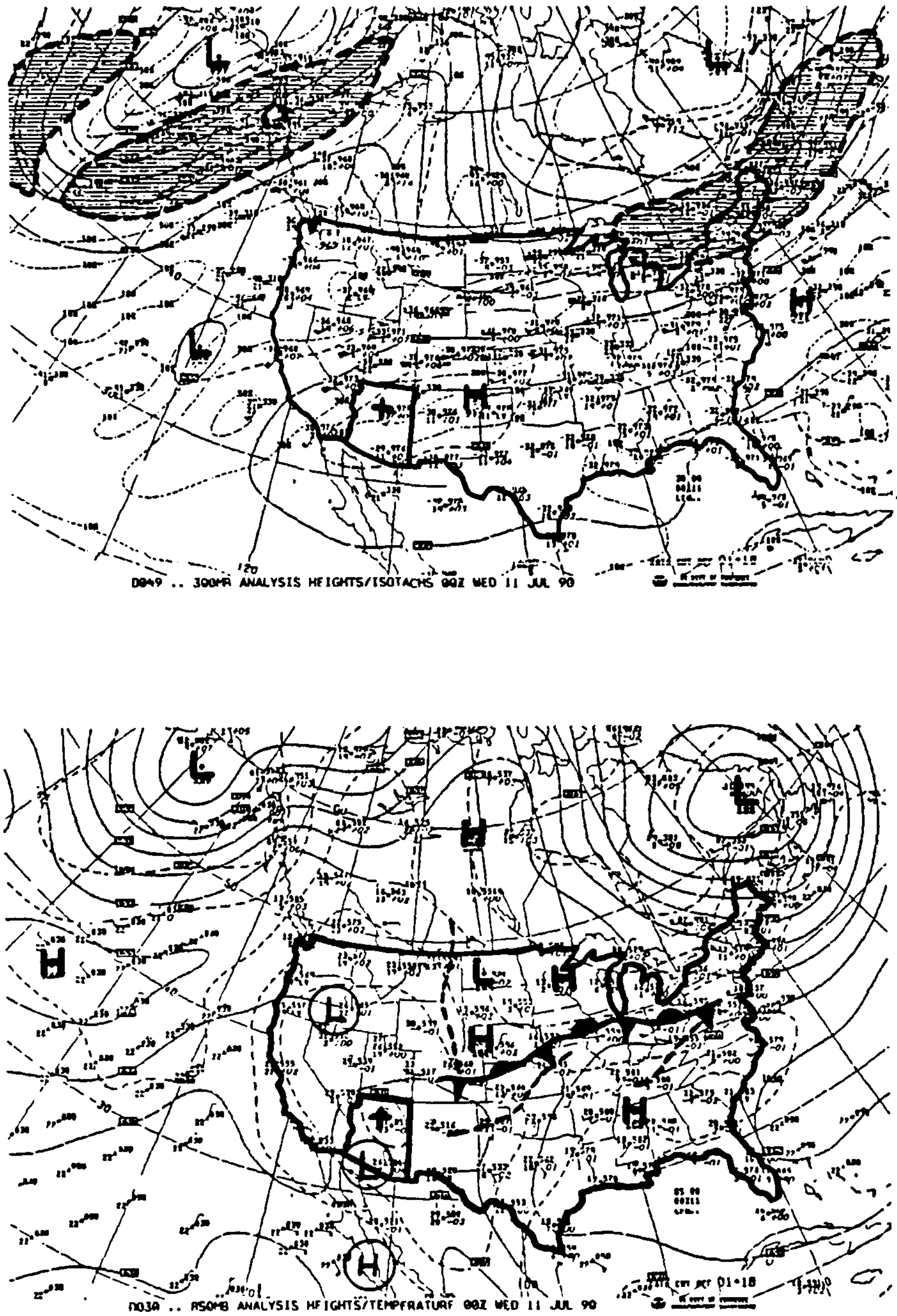
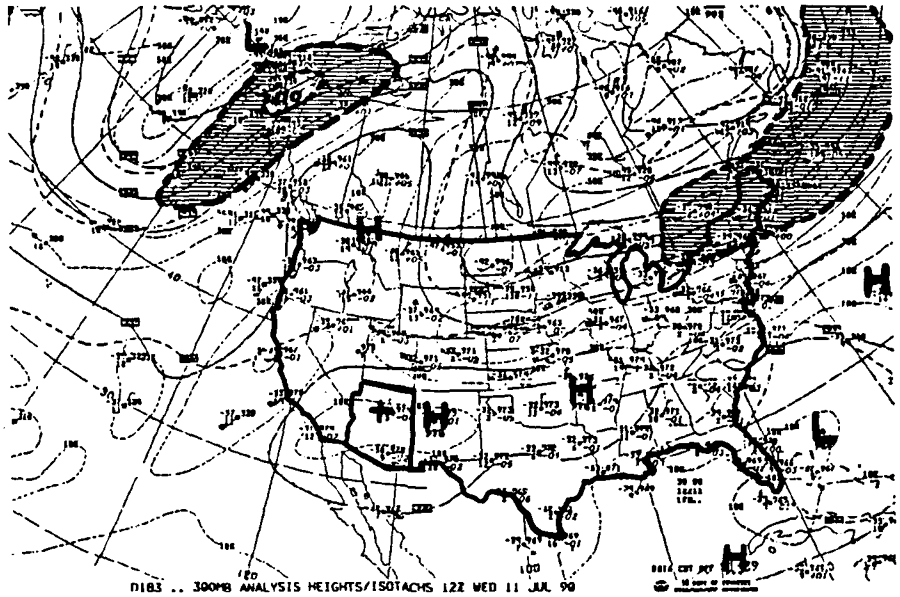


Fig 10. NWS 850 (bottom) and 300 (top) mb Charts: July 11, 0000 UTC



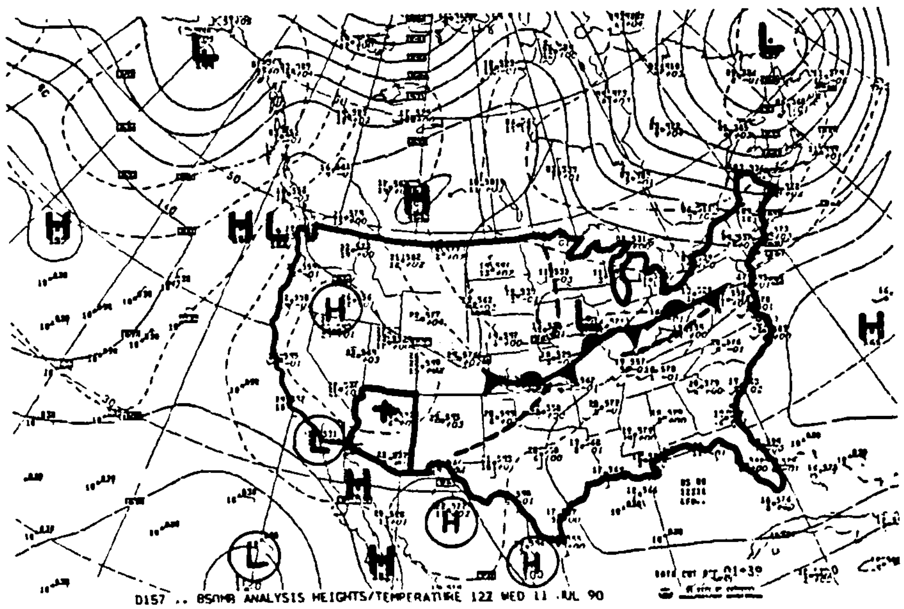


Fig 11. NWS 850 (bottom) and 300 (top) mb Charts: July 11, 1200 UTC

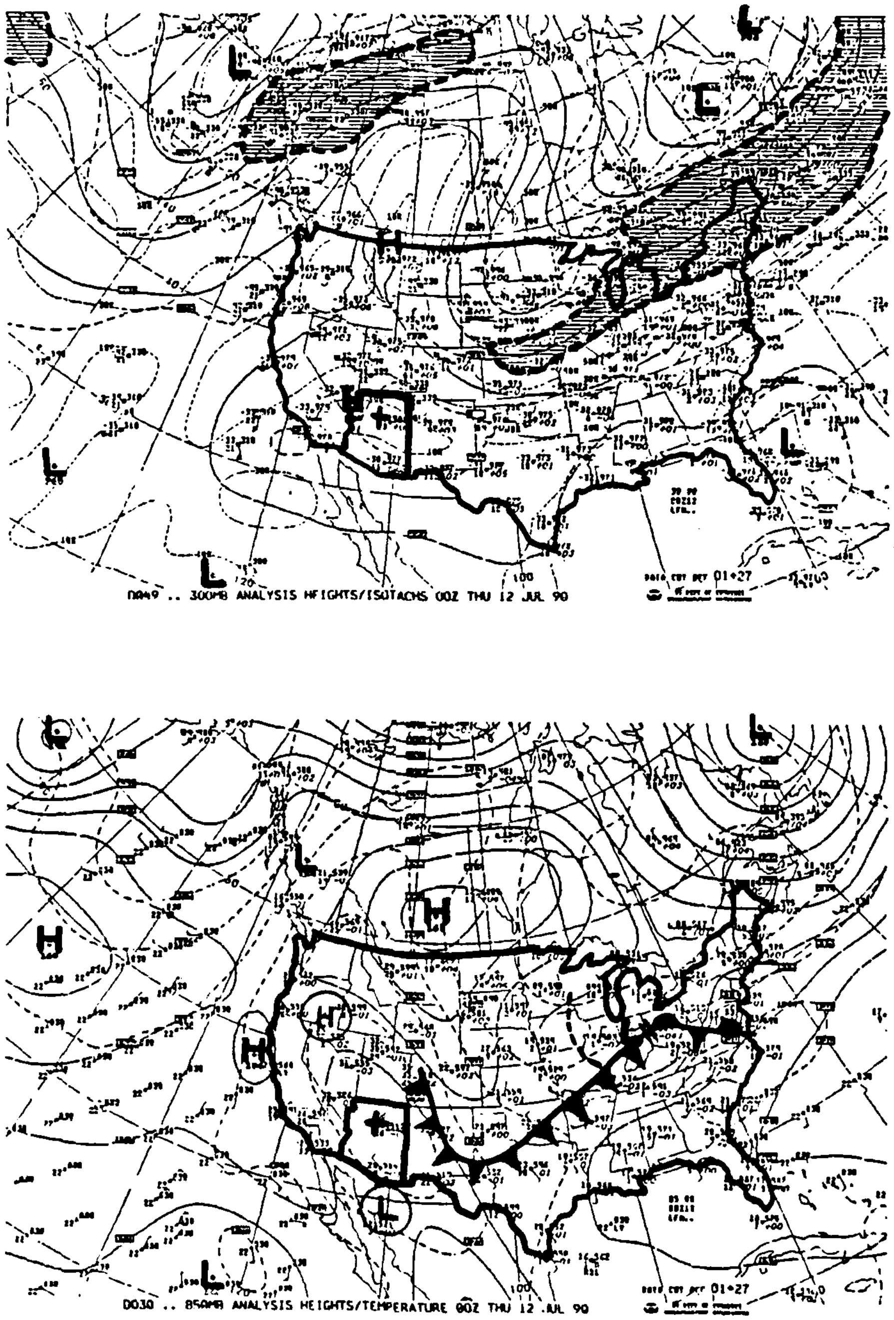


Fig 12. NWS 850 (bottom) and 300 (top) mb Charts: July 12, 0000 UTC

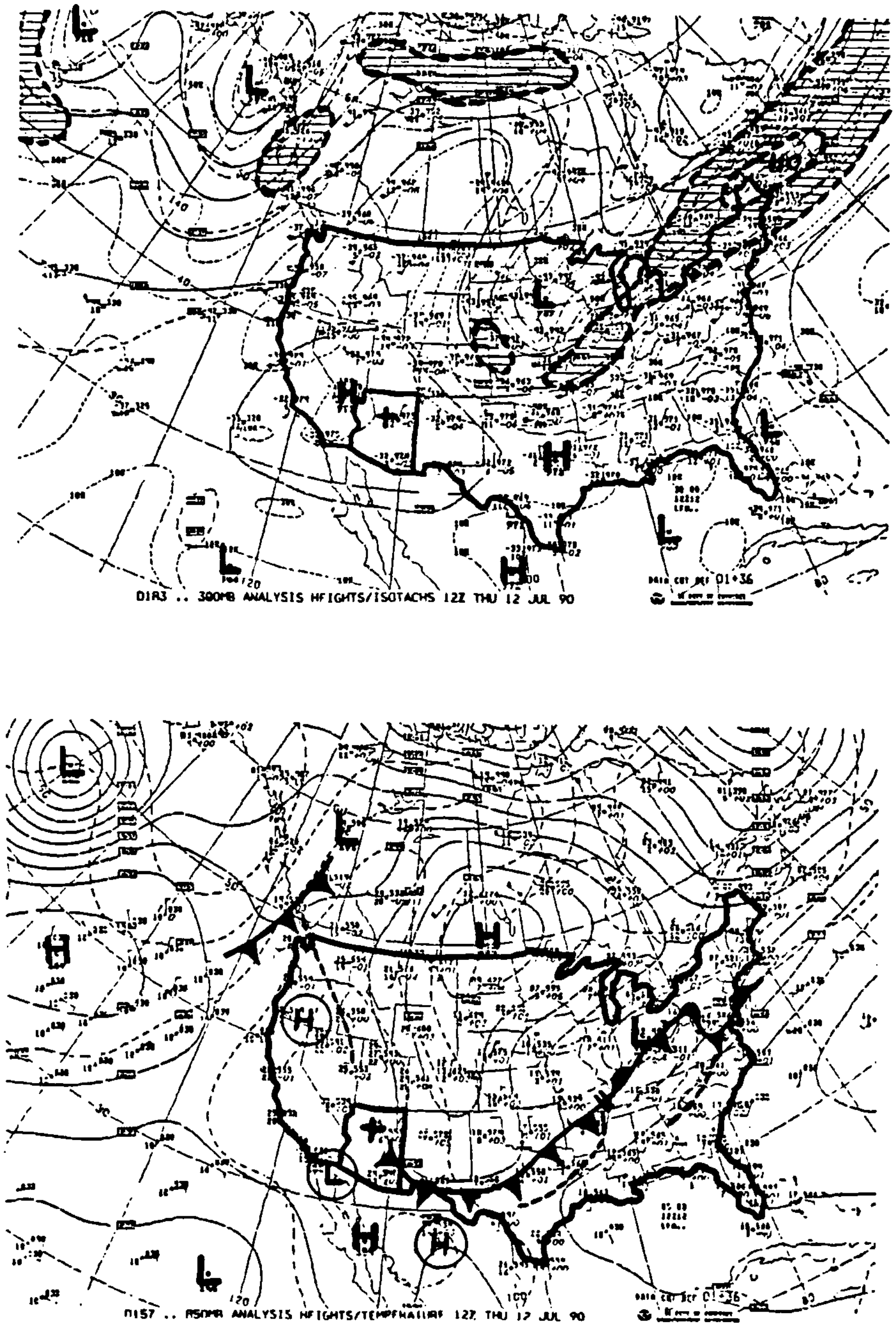


Fig 13. NWS 850 (bottom) and 300 (top) mb Charts: July 12, 1200 UTC

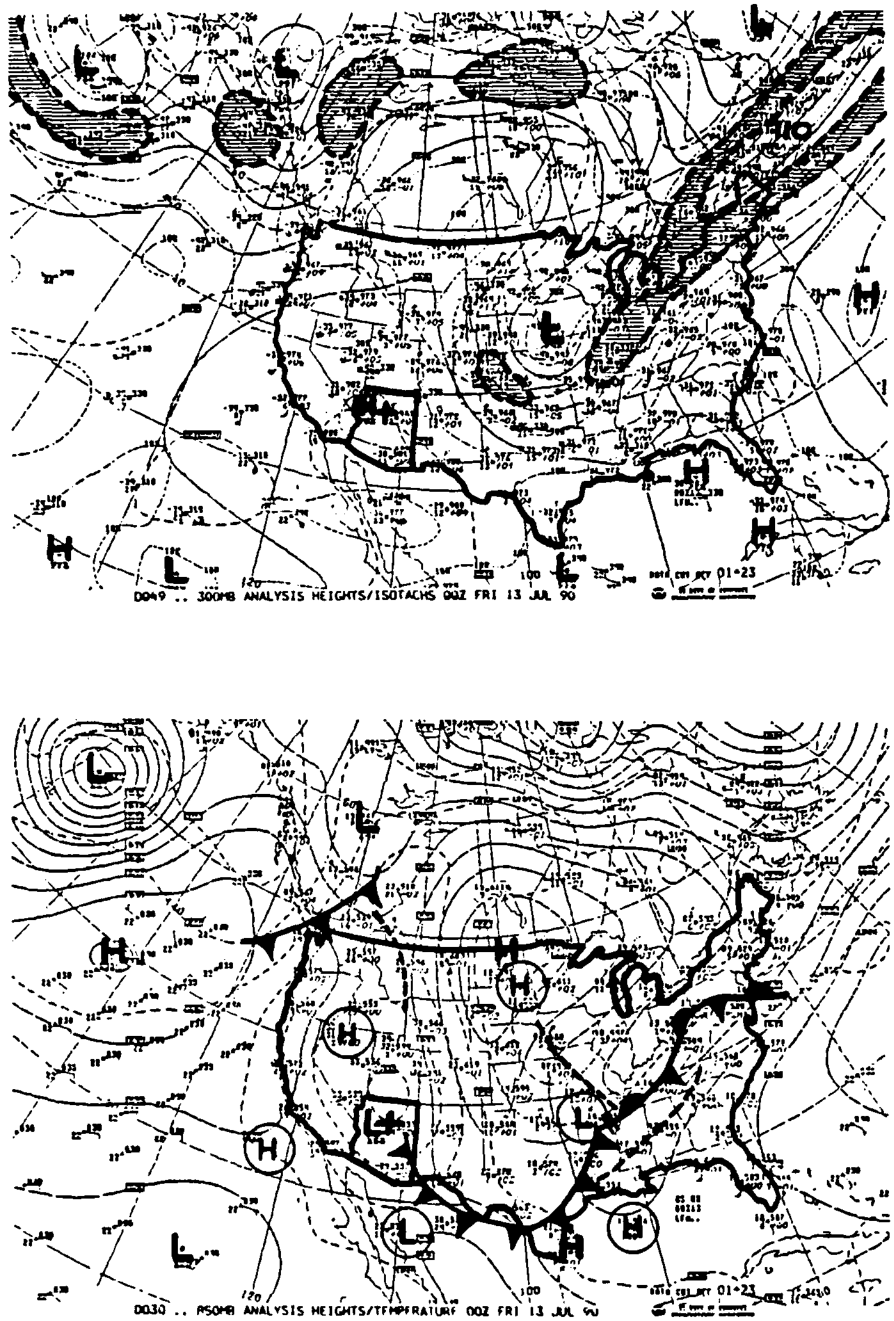
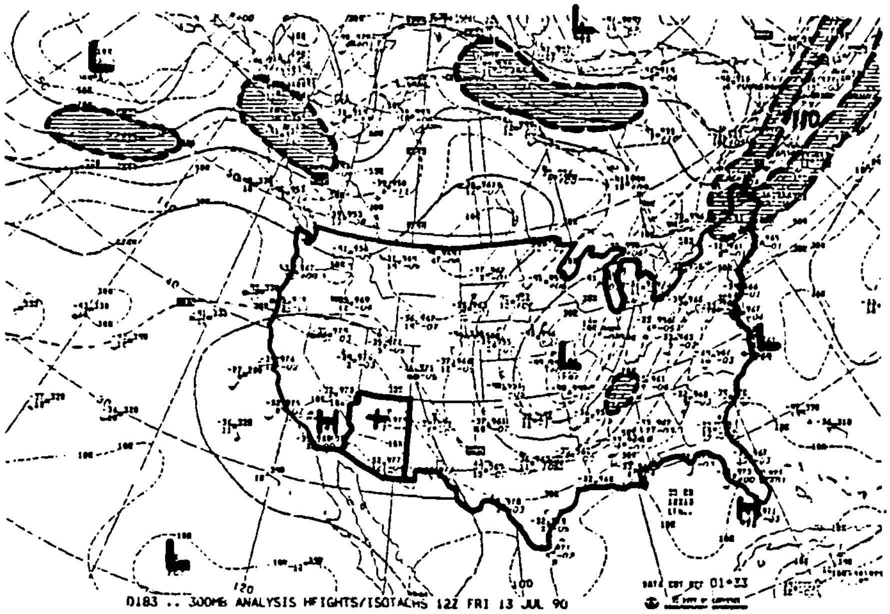


Fig 14. NWS 850 (bottom) and 300 (top) mb Charts: July 13, 0000 UTC



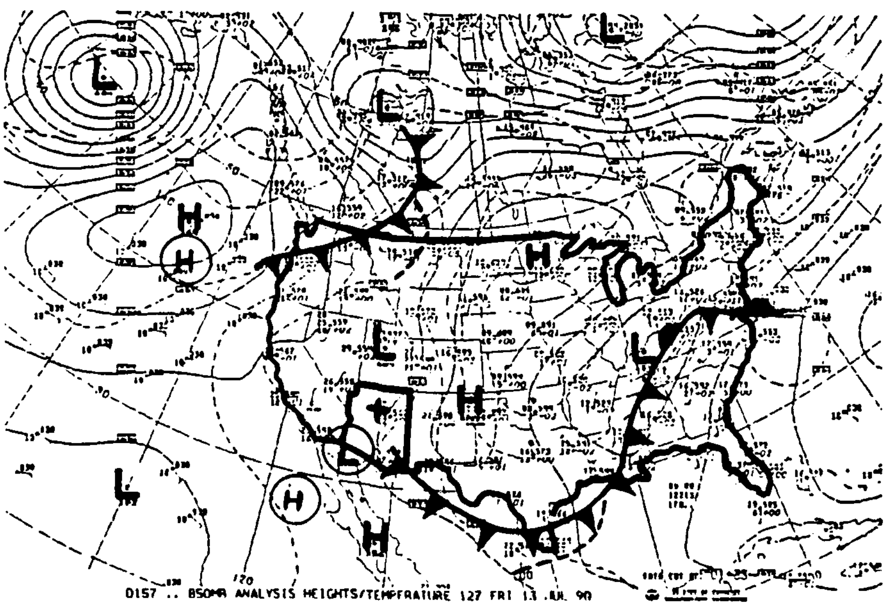


Fig 15. NWS 850 (bottom) and 300 (top) mb Charts: July 13, 1200 UTC

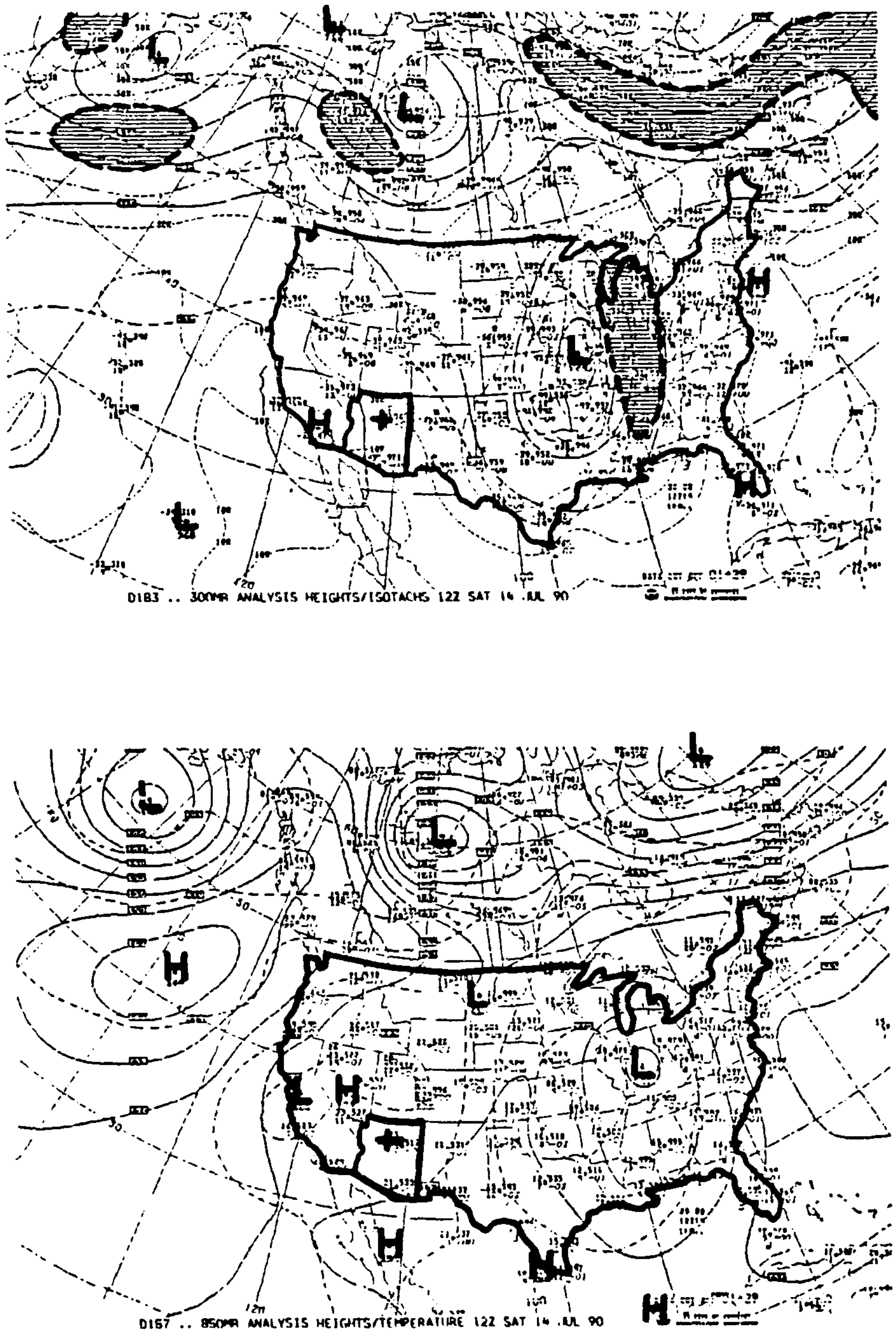


Fig 16. NWS 850 (bottom) and 300 (top) mb Charts: July 14, 1200 UTC

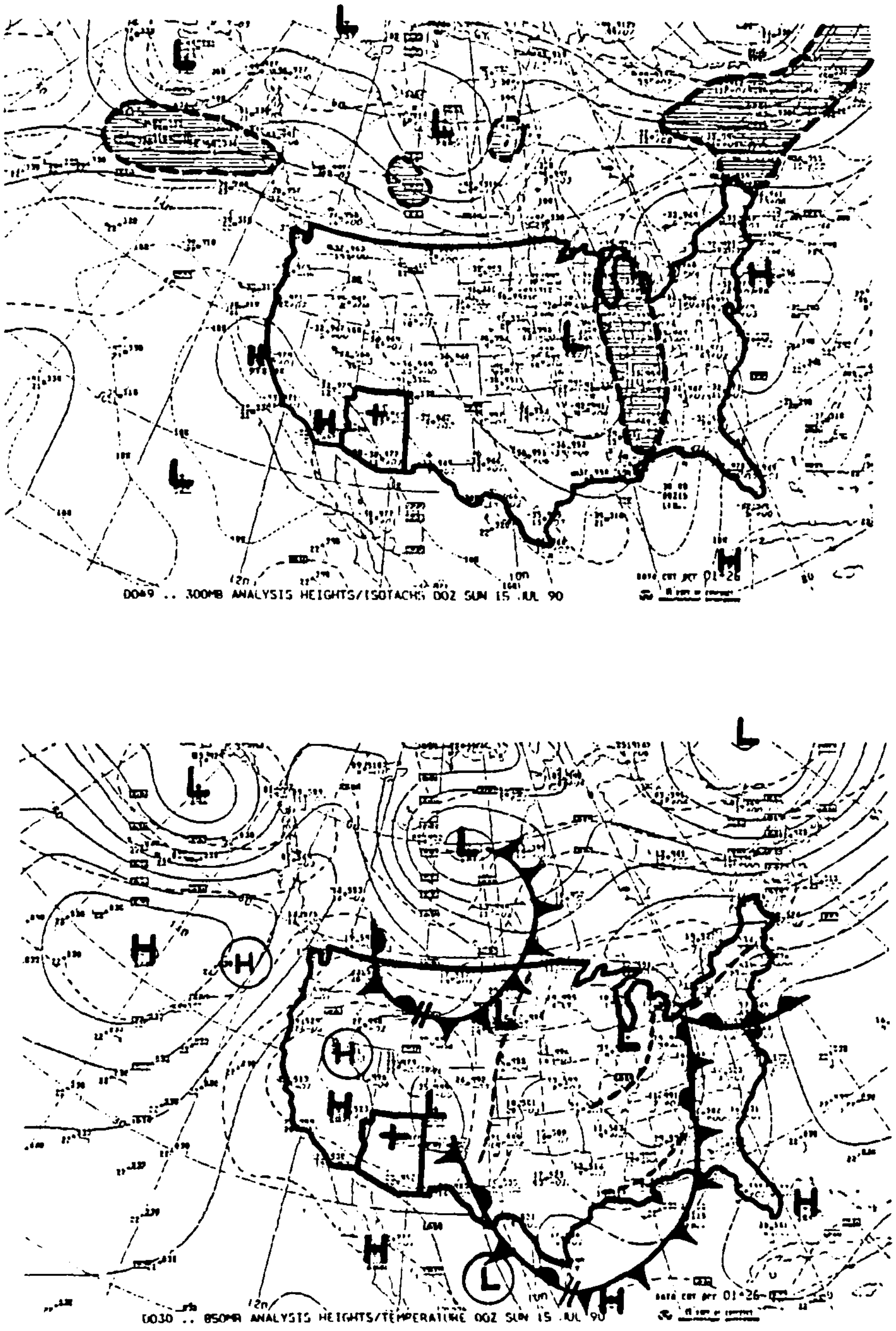


Fig 17. NWS 850 (bottom) and 300 (top) mb Charts: July 15, 0000 UTC

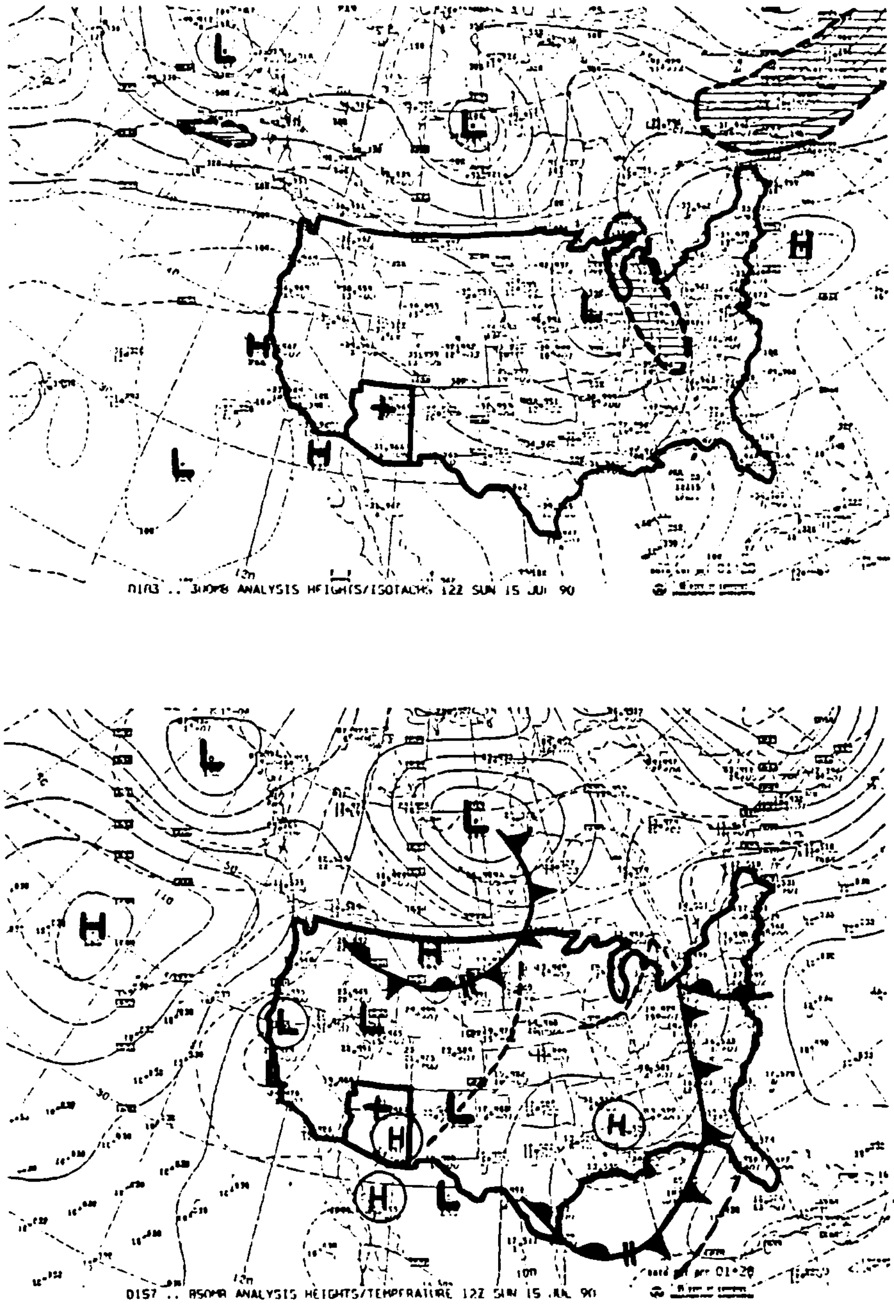
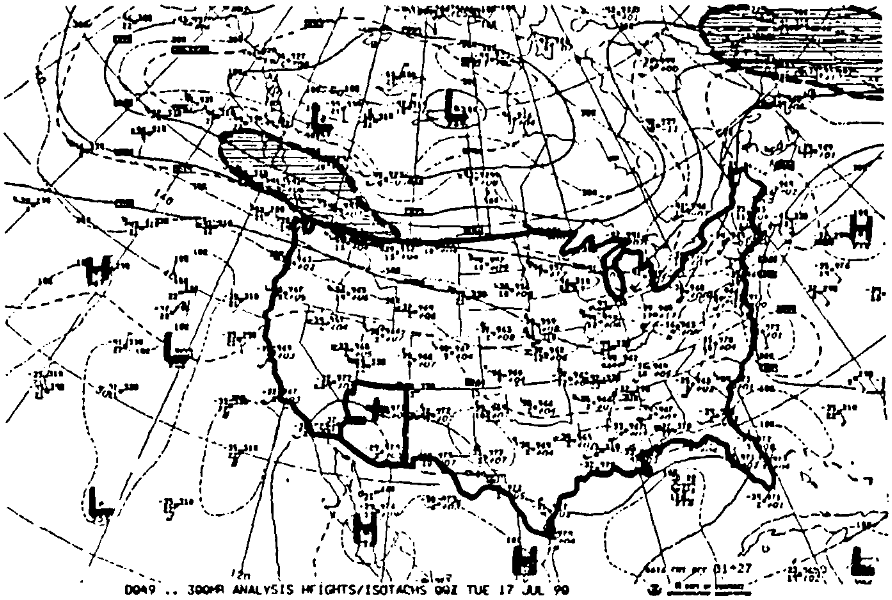


Fig 18. NWS 850 (bottom) and 300 (top) mb Charts: July 15, 1200 UTC



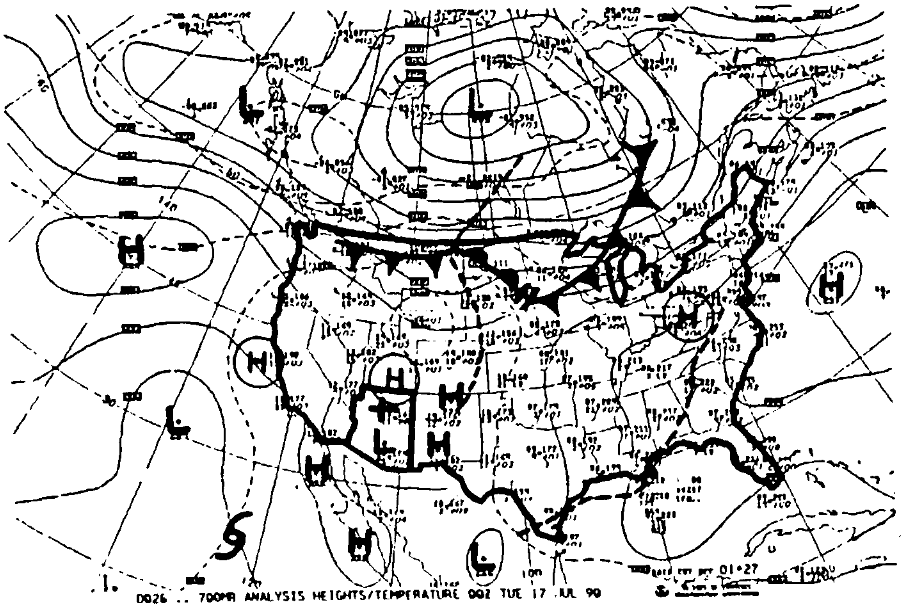


Fig 19. NWS 700 (bottom) and 300 (top) mb Charts: July 17, 0000 UTC

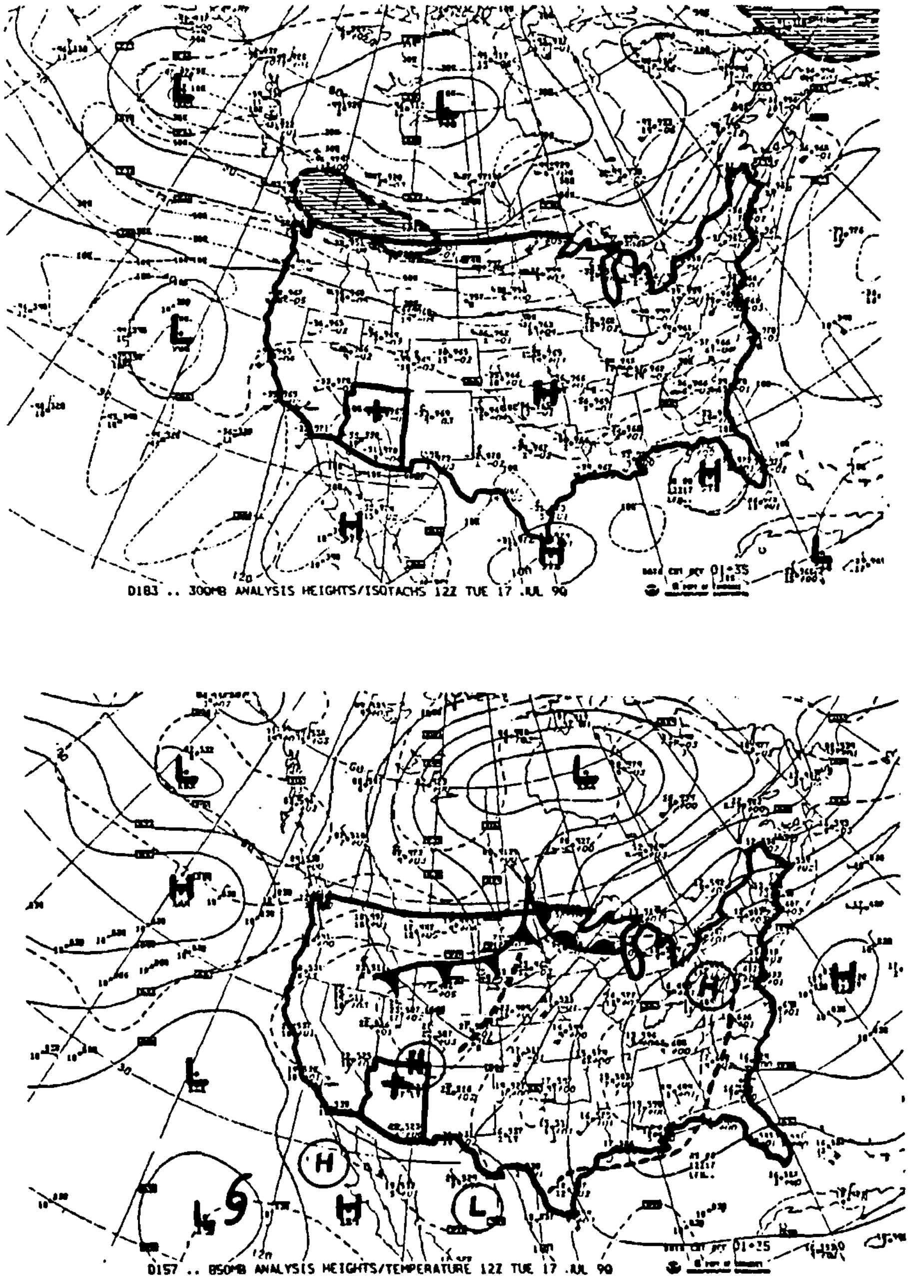
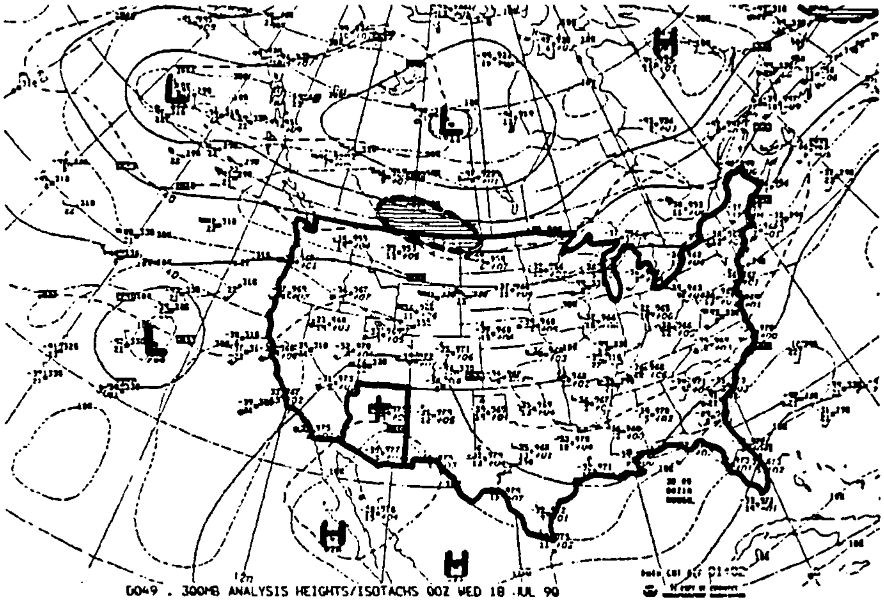


Fig 20. NWS 850 (bottom) and 300 (top) mb Charts: July 17, 1200 UTC



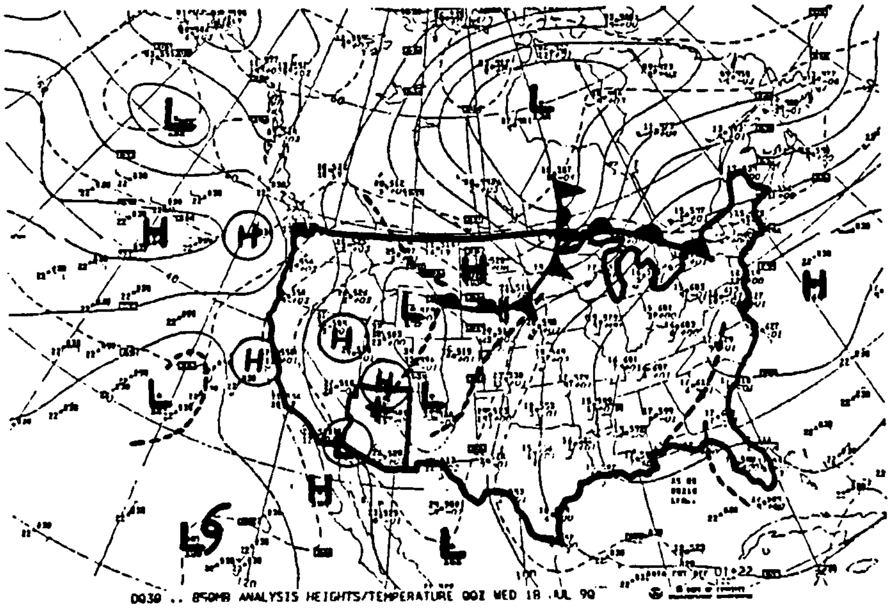
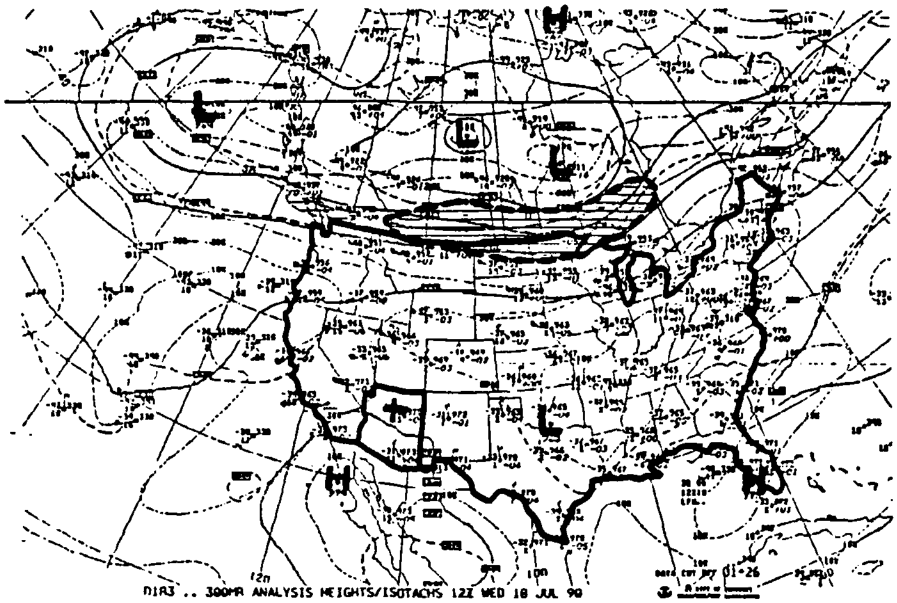


Fig 21. NWS 850 (bottom) and 300 (top) mb Charts: July 18, 0000 UTC



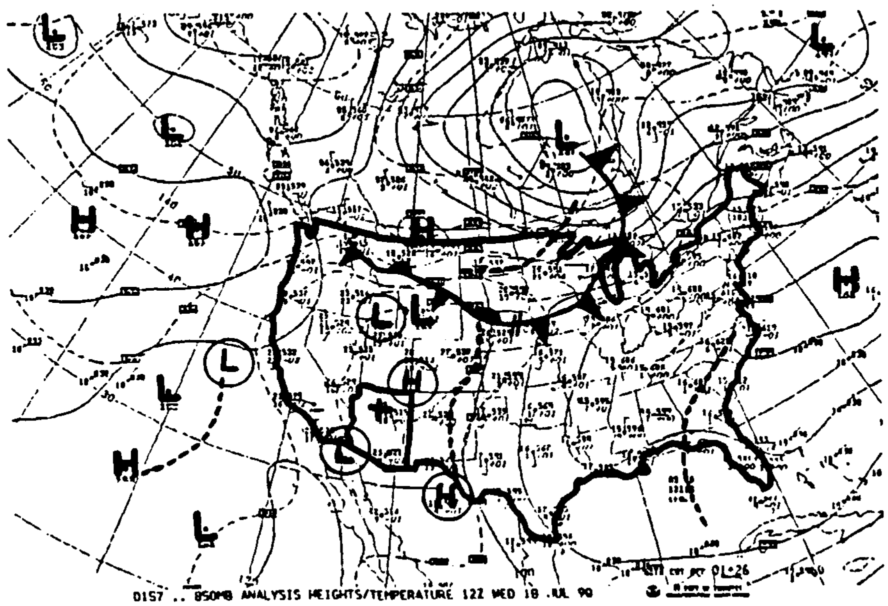


Fig 22. NWS 850 (bottom) and 300 (top) mb Charts: July 18, 1200 UTC

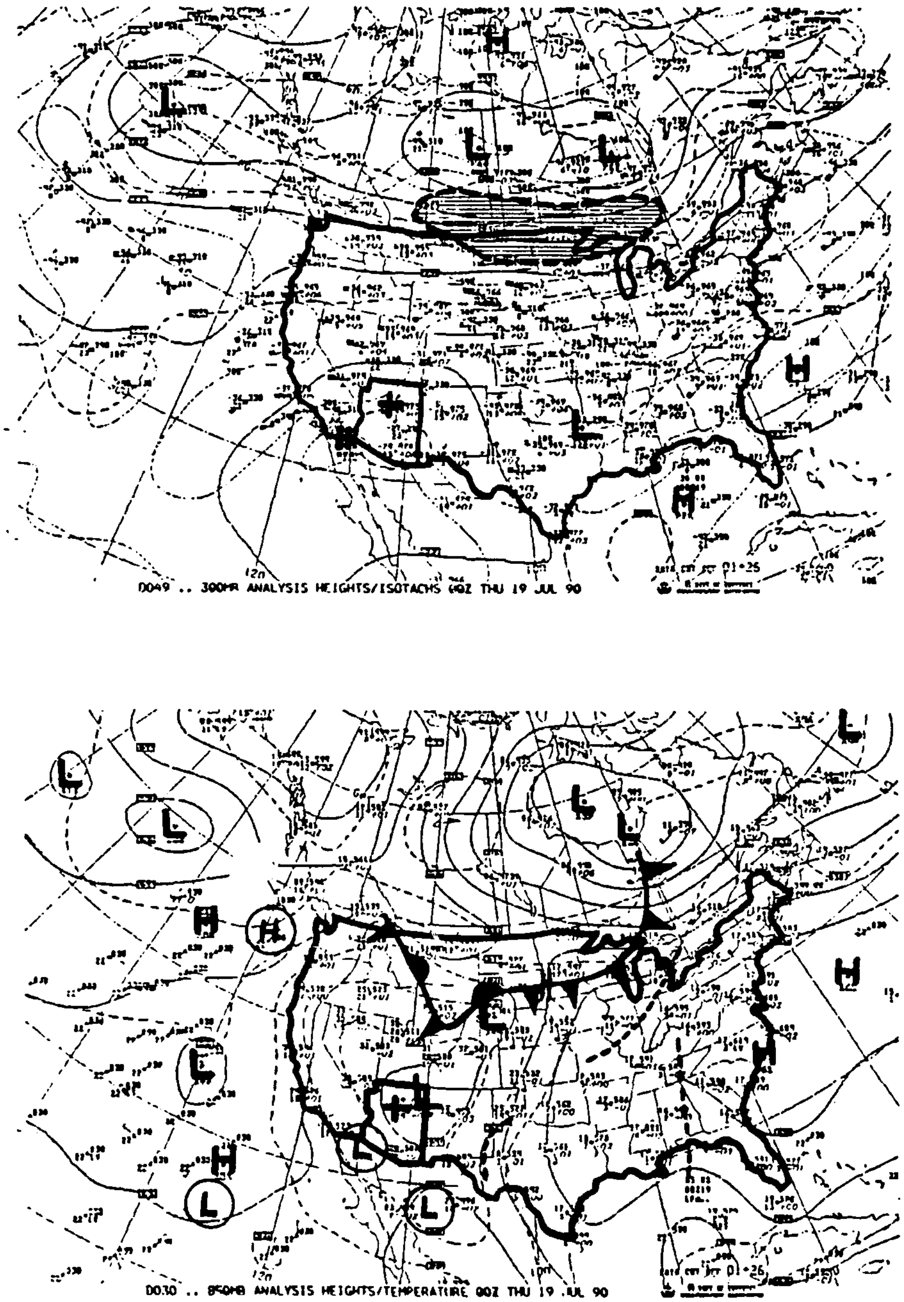


Fig 23. NWS 850 (bottom) and 300 (top) mb Charts: July 19, 0000 UTC

APPENDIX C. PROCESSED OPTICAL DATA (1990 July 10-19)

Appendix C displays nightly plots of all processed transverse coherence length (r_o) and isoplanatic angle (θ_o) data sampled between 10-19 July 1990. The optical wavelength is 500 nm. Due to hardware problems, θ_o measurements commenced on 13 July 1990.

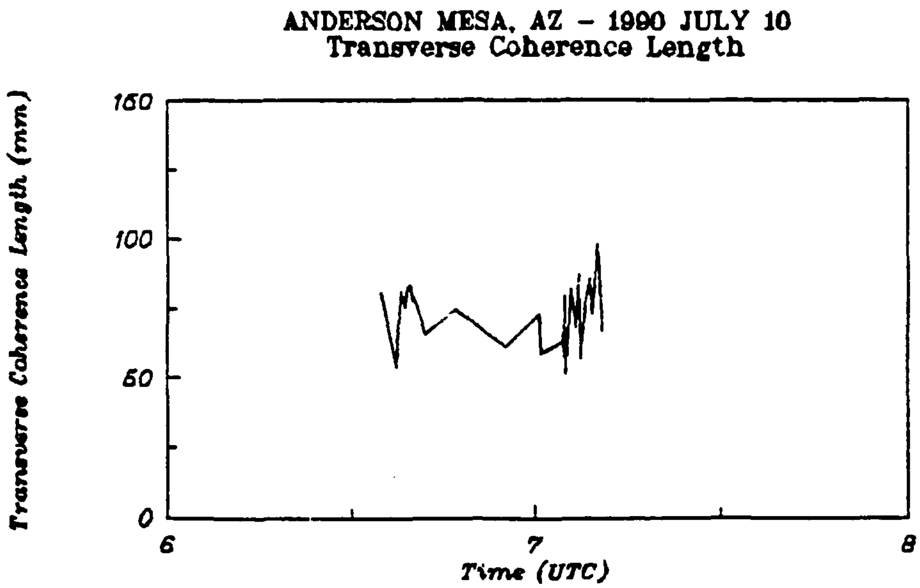


Fig 24. Anderson Mesa, Az Optical Data: 1990 July 10

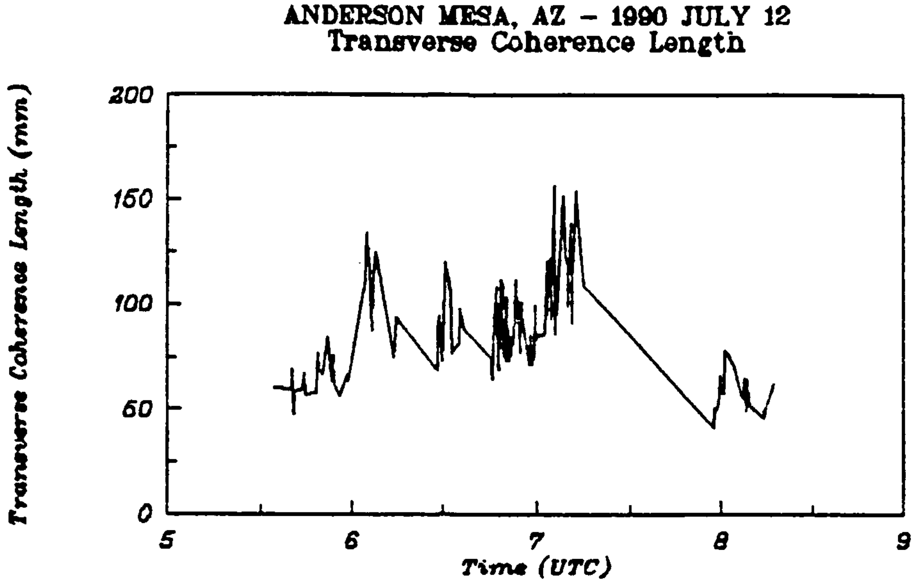


Fig 25. Anderson Mesa, Az Optical Data: 1990 July 12

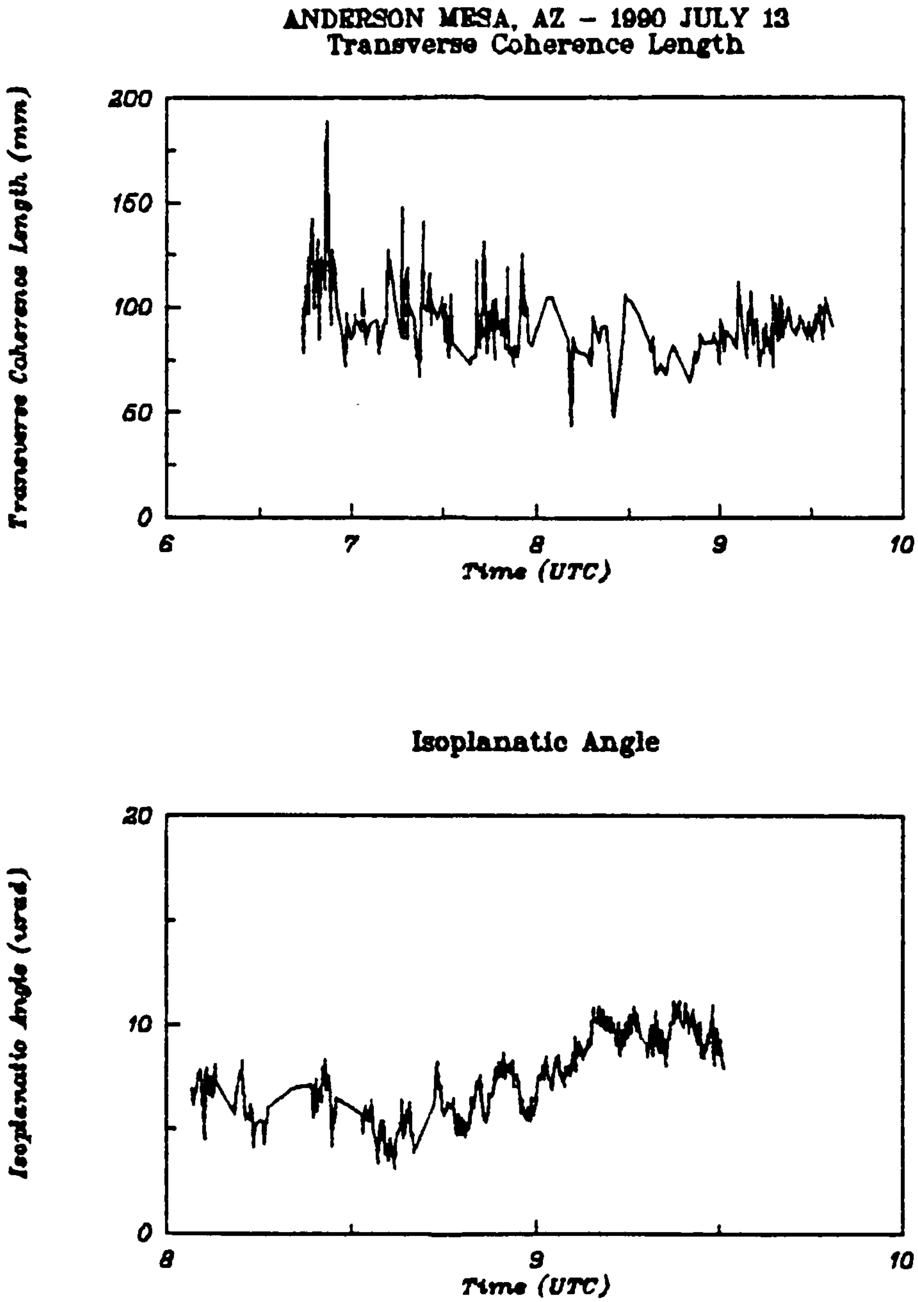
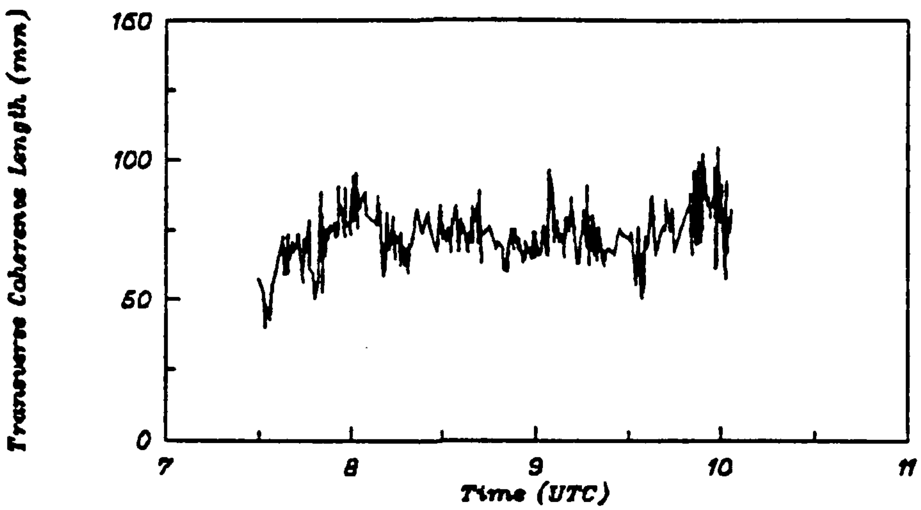


Fig 26. Anderson Mesa, Az Optical Data: 1990 July 13

ANDERSON MESA, AZ - 1990 JULY 15
Transverse Coherence Length



Isoplanatic Angle

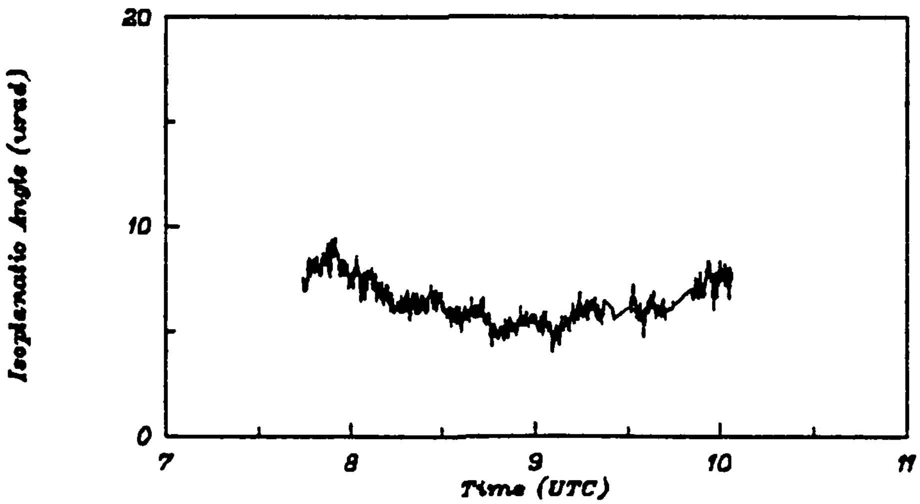
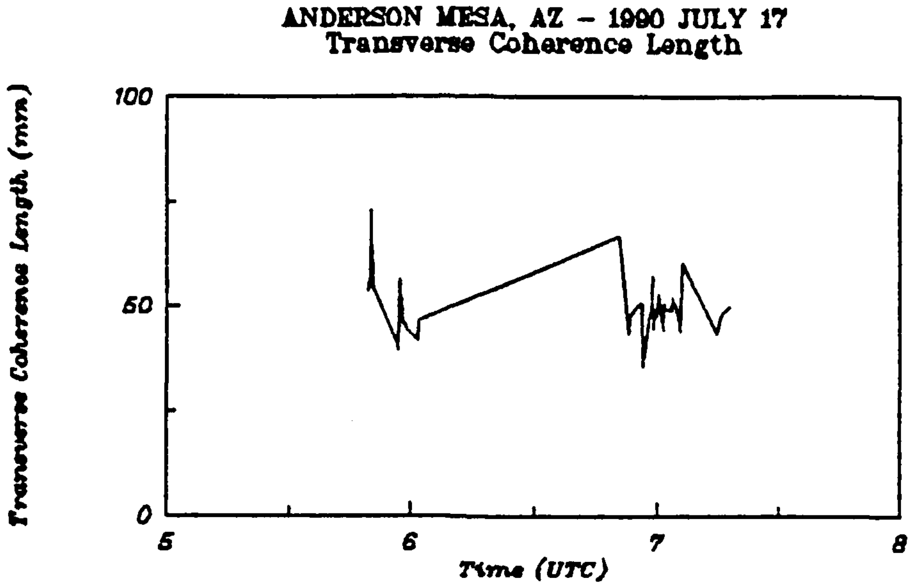


Fig 27. Anderson Mesa, Az Optical Data: 1990 July 15



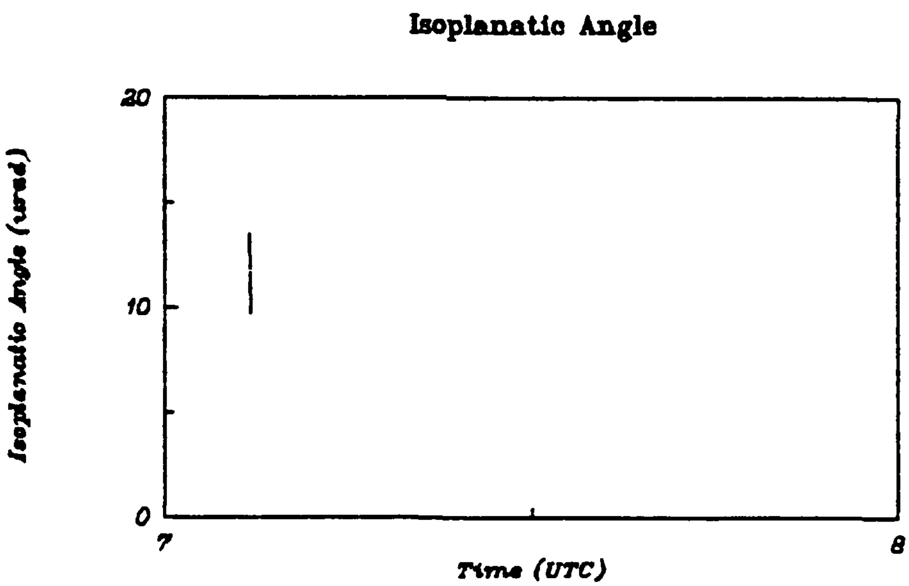
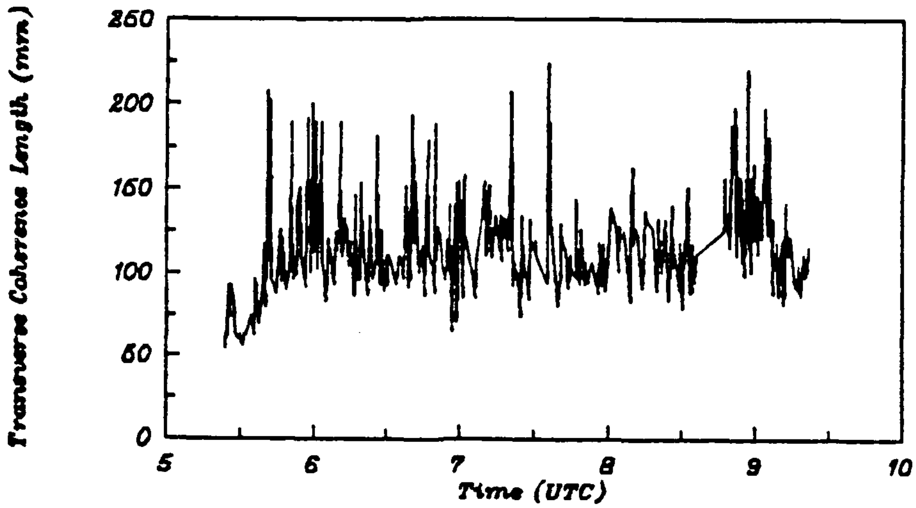


Fig 28. Anderson Mesa, Az Optical Data: 1990 July 17

ANDERSON MESA, AZ – 1990 JULY 18
Transverse Coherence Length



Isoplanatic Angle

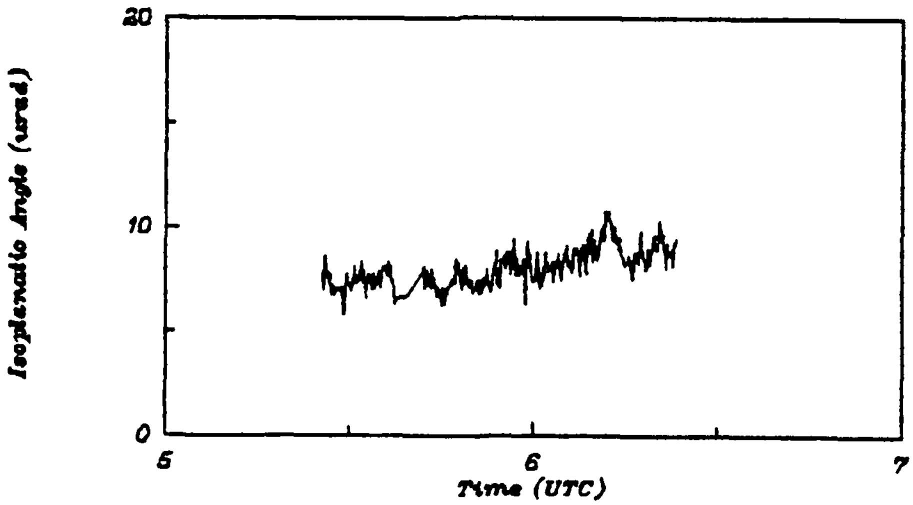


Fig 29. Anderson Mesa, Az Optical Data: 1990 July 18

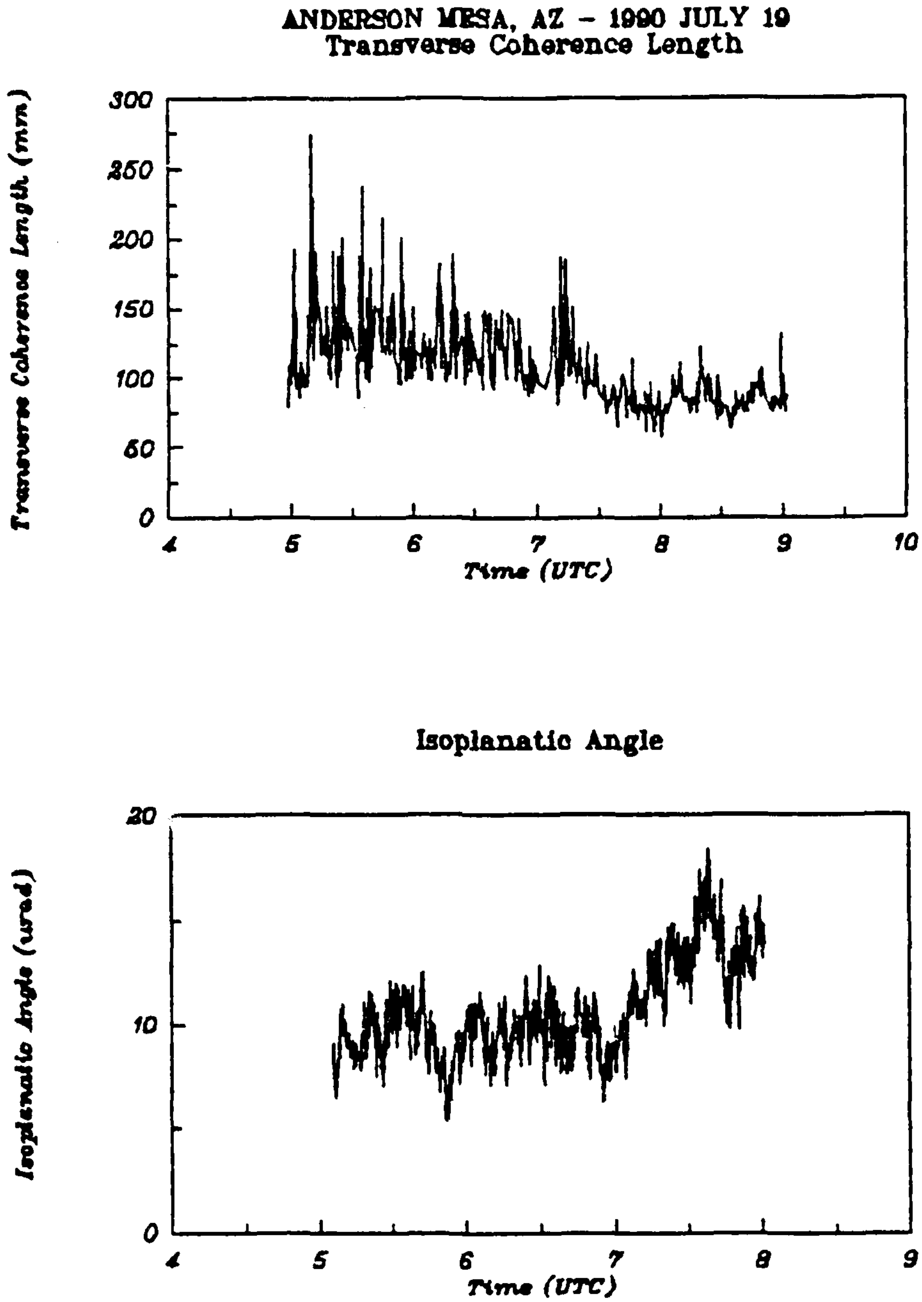


Fig 30. Anderson Mesa, Az Optical Data: 1990 July 19

APPENDIX D. TRANSVERSE COHERENCE LENGTH STATISTICS

Appendix D presents the transverse coherence length (r_o) un-normalized percent frequency distribution for each night-time session (bin interval is 10 mm). Empirical seeing quality histograms are also included. The bin intervals selected for this qualitative interpretation are a product of approximately 50 site surveys spanning 18-40 degrees latitude and 65-156 degrees longitude. The specific empirical seeing quality intervals are:

Empirical Seeing Quality	r_o measurement (mm)
Poor	00 - 50
Mediocre	51 - 100
Good	101 - 200
Very Good	201 - 300
Excellent	301 - 500

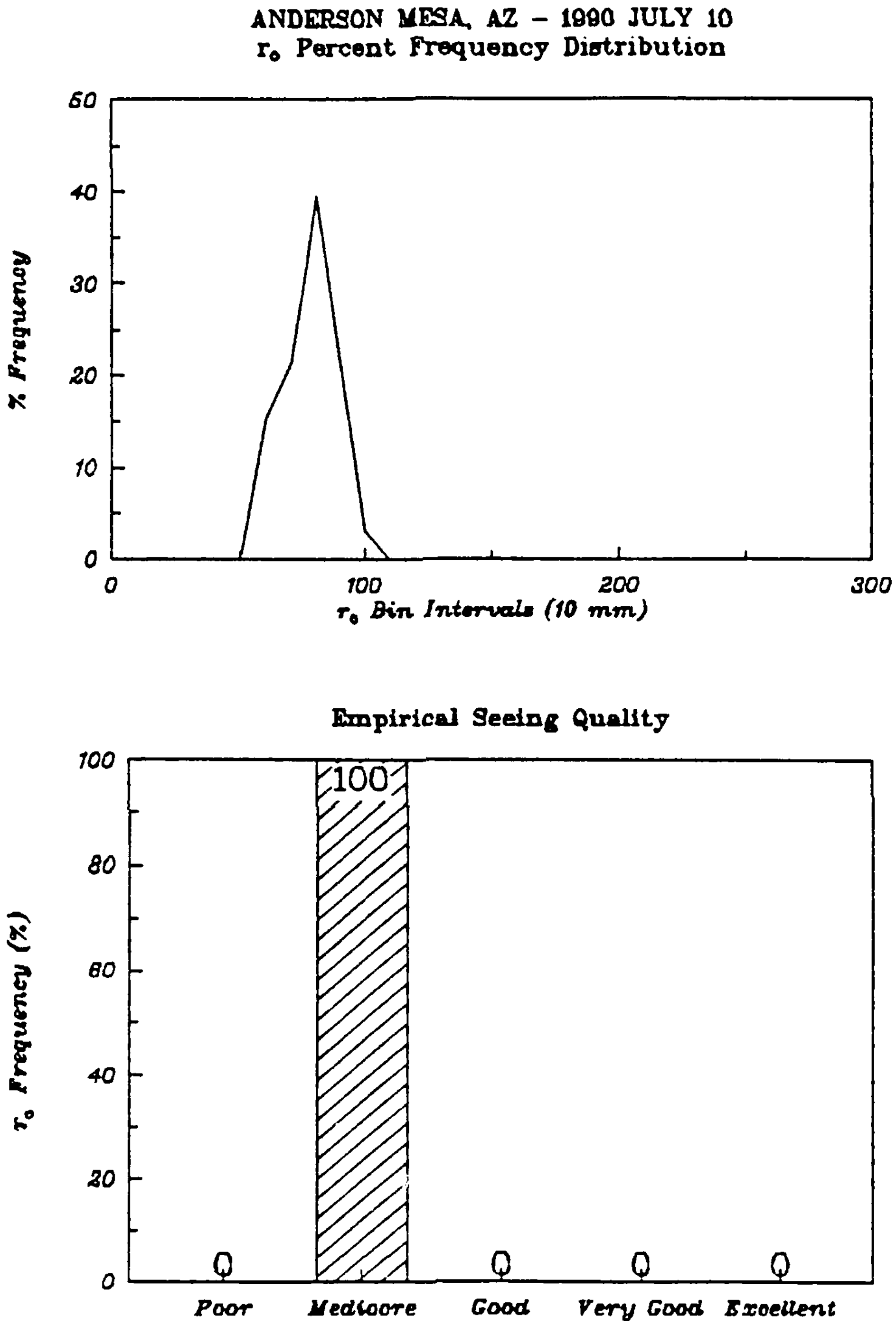
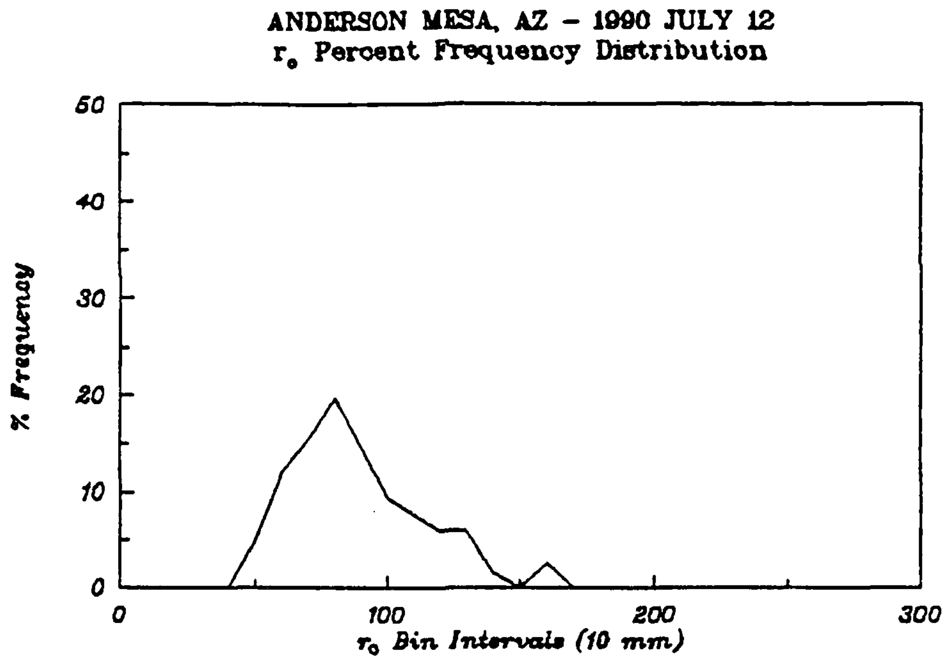


Fig 31. Anderson Mesa, Az r_o Statistics: 1990 July 10



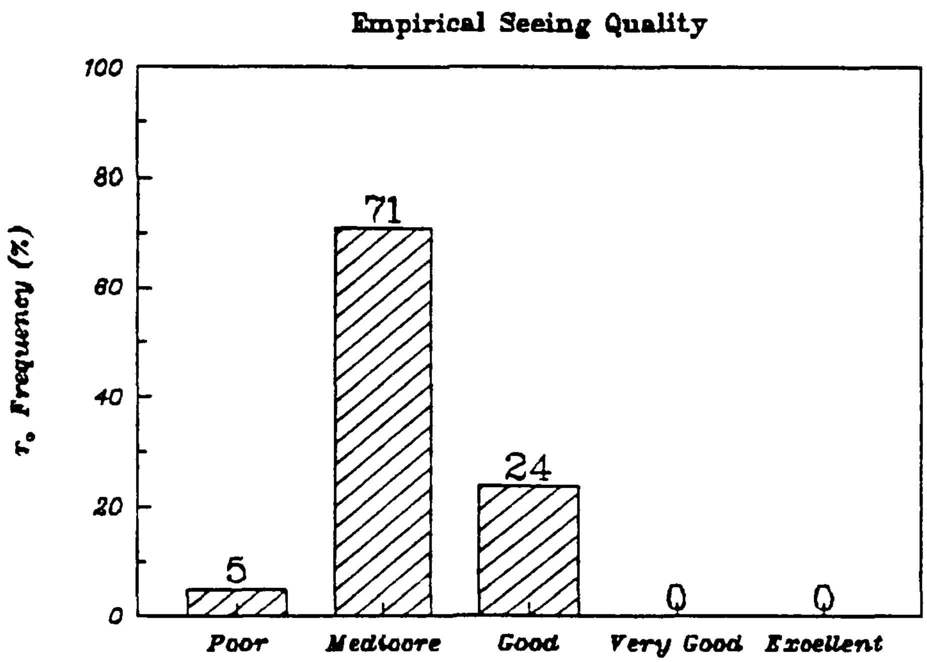
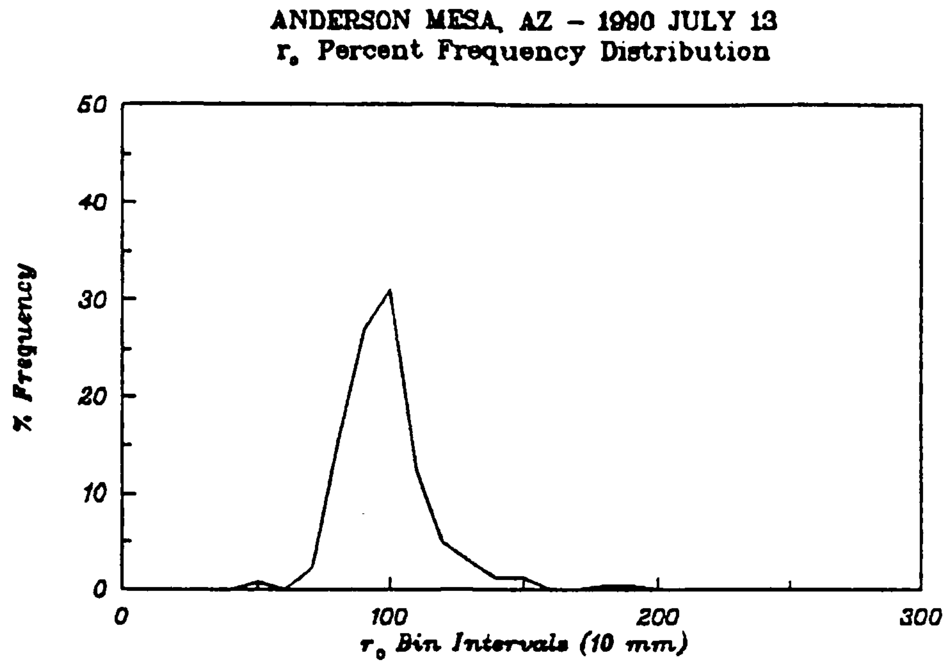


Fig 32. Anderson Mesa, Az r_o Statistics: 1990 July 12



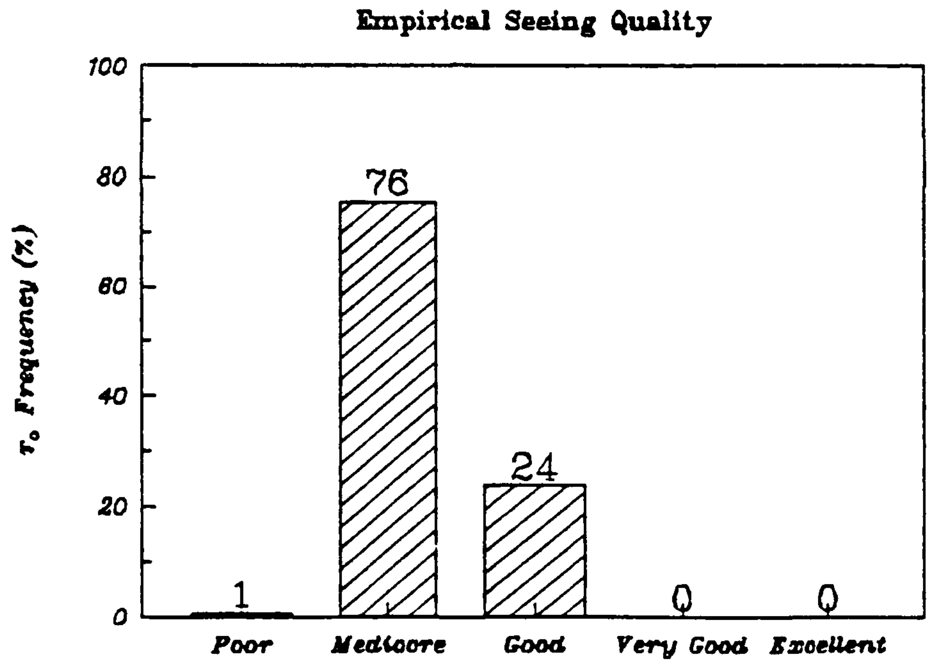
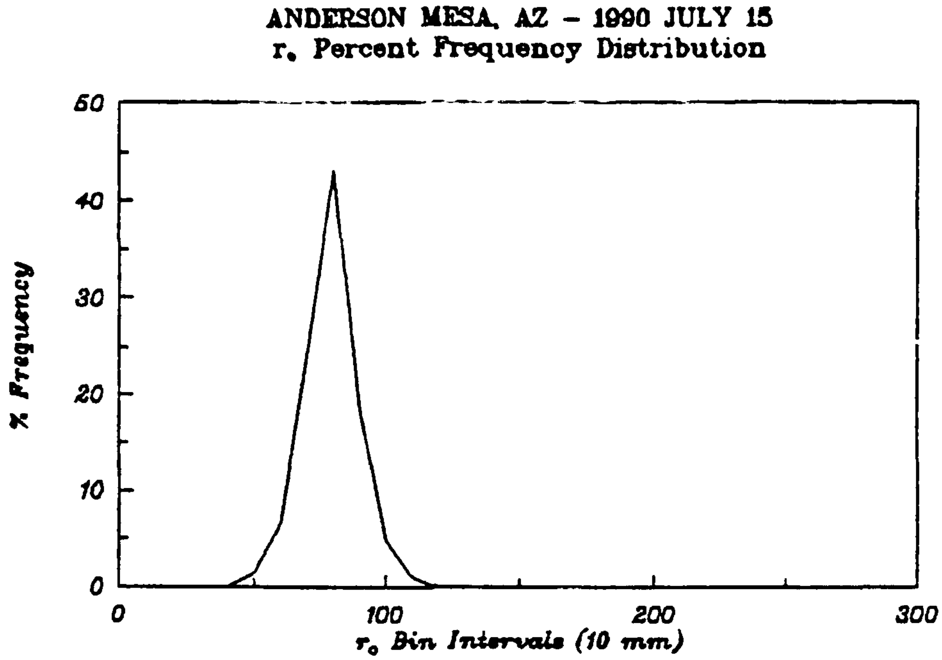


Fig 33. Anderson Mesa, Az r_o Statistics: 1990 July 13



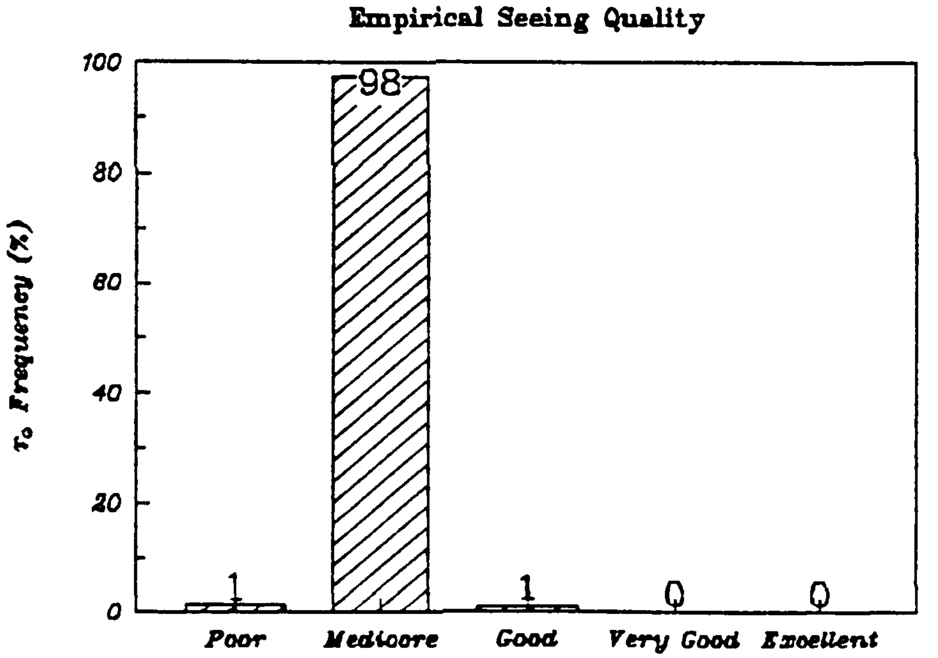
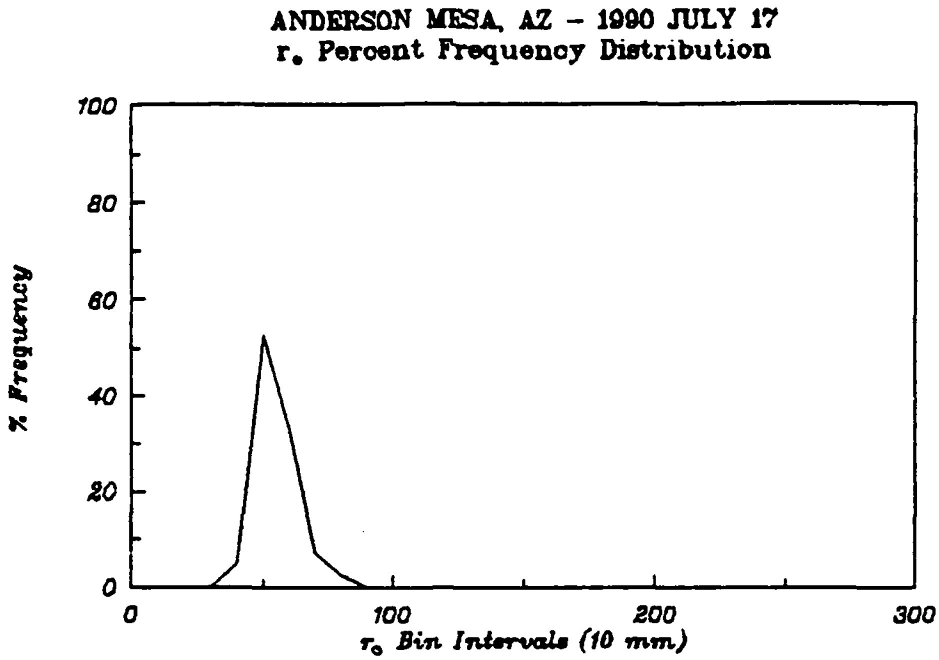


Fig 34. Anderson Mesa, Az r_o Statistics: 1990 July 15



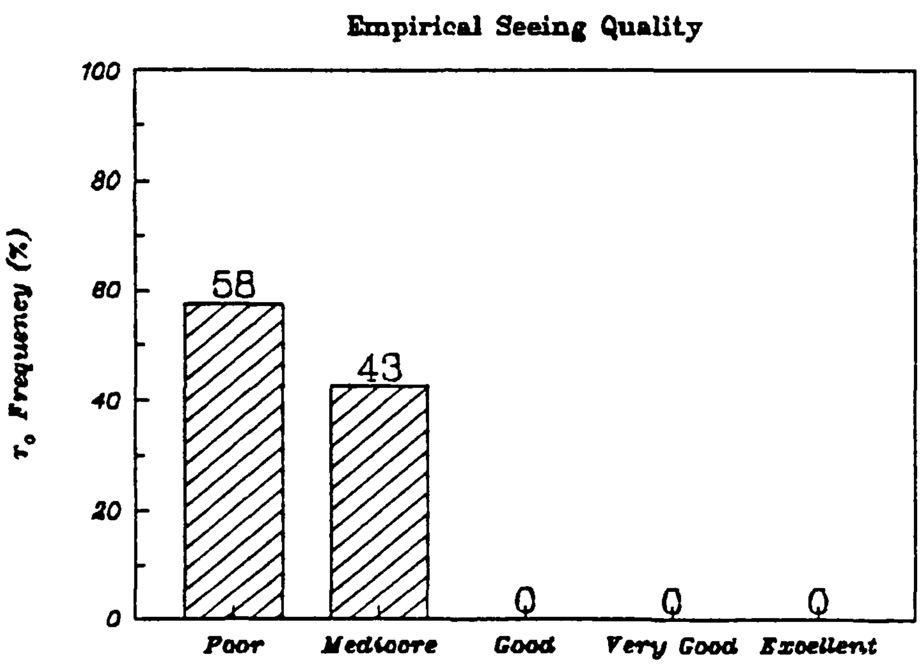
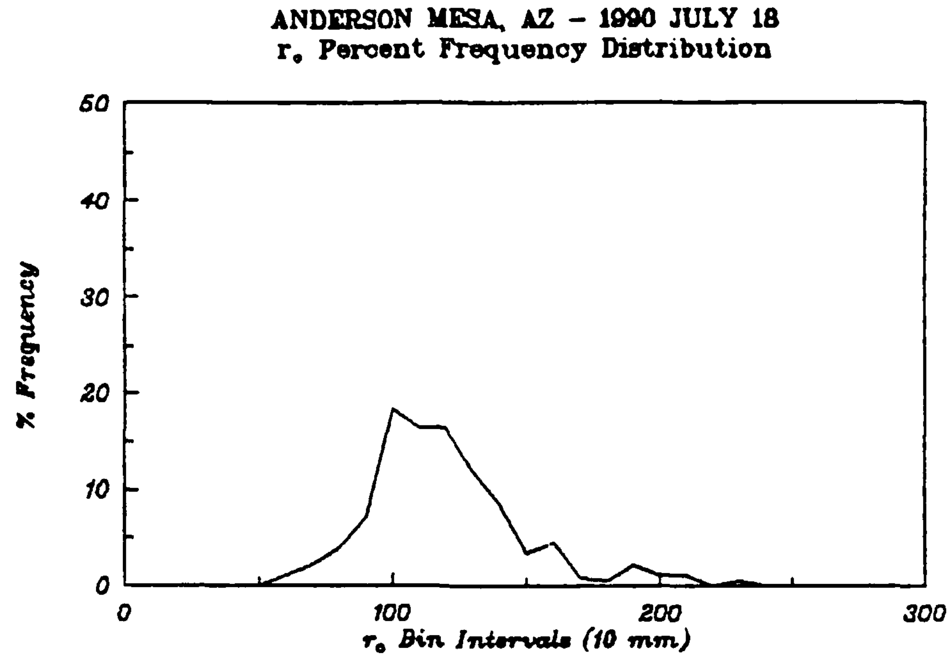


Fig 35. Anderson Mesa, Az r_o Statistics: 1990 July 17



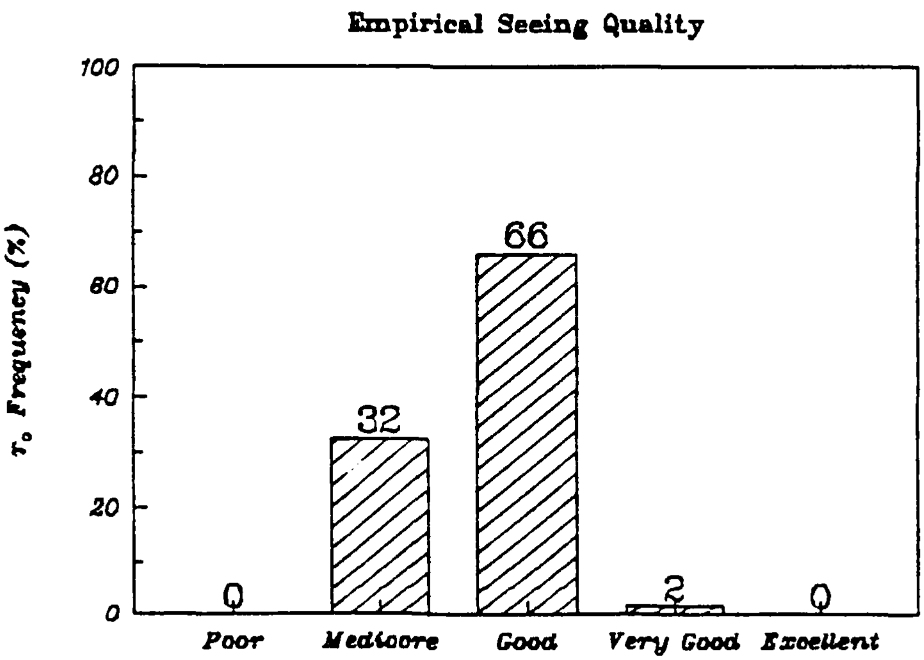
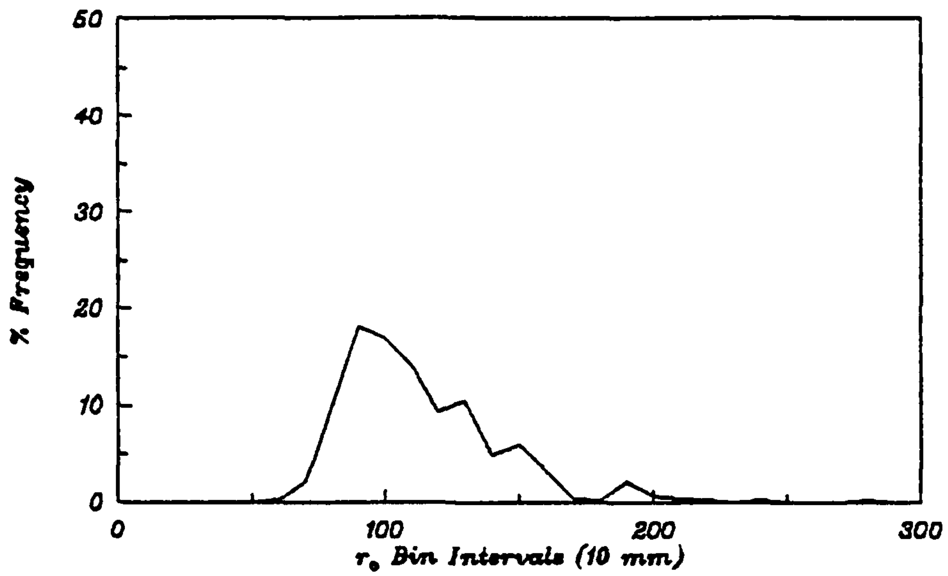


Fig 36. Anderson Mesa, Az r_o Statistics: 1990 July 18

ANDERSON MESA, AZ - 1990 JULY 19
r_o Percent Frequency Distribution



Empirical Seeing Quality

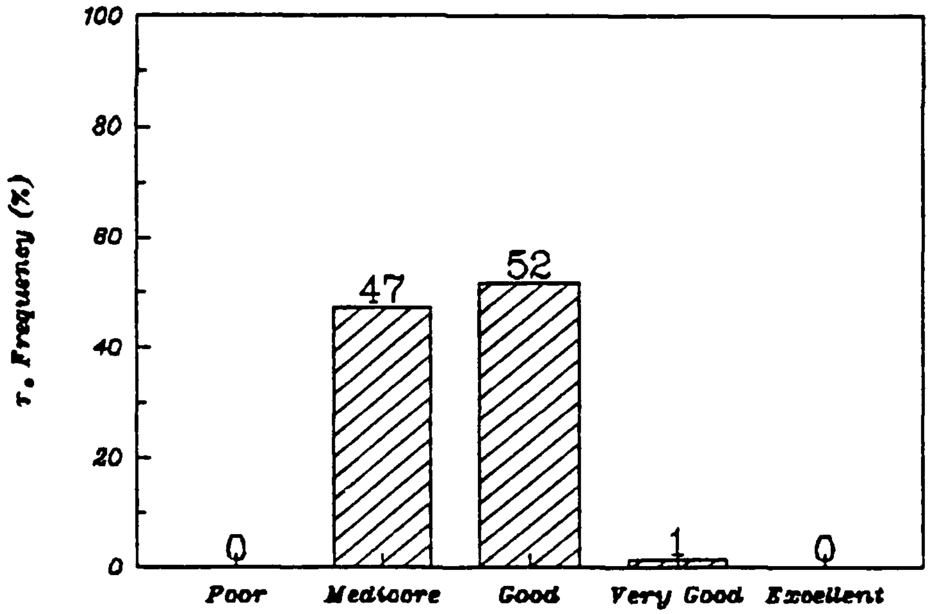
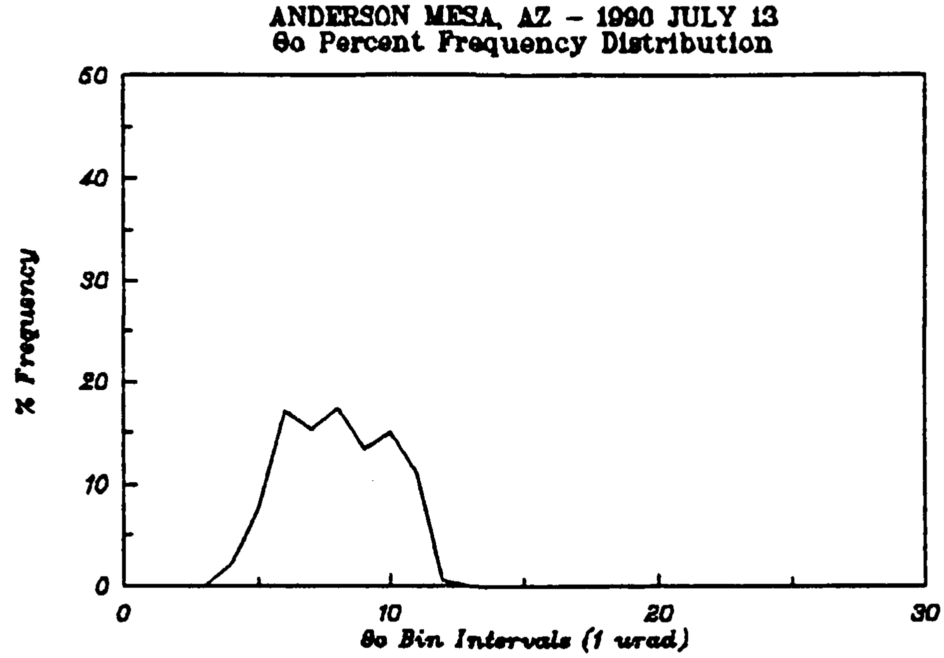


Fig 37. Anderson Mesa, Az r_o Statistics: 1990 July 19

APPENDIX E. ISOPLANATIC ANGLE STATISTICS

To facilitate the interpretation of isoplanatic angle (θ_o) measurements, Appendix E provides an un-normalized frequency distribution and an empirical seeing quality plot for each sampling session. The bin-size for the frequency distribution is 1 urad. The empirical seeing quality graphs use the following experience-derived bin intervals:

Empirical Seeing Quality	θ_o measurement (urad)
Very Poor	0 - 4.0
Poor	4.1 - 8.0
Mediocre	8.1 - 12.0
Good	12.1 - 20.0
Very Good	20.1 - 30.0
Excellent	30.1 - 50.0



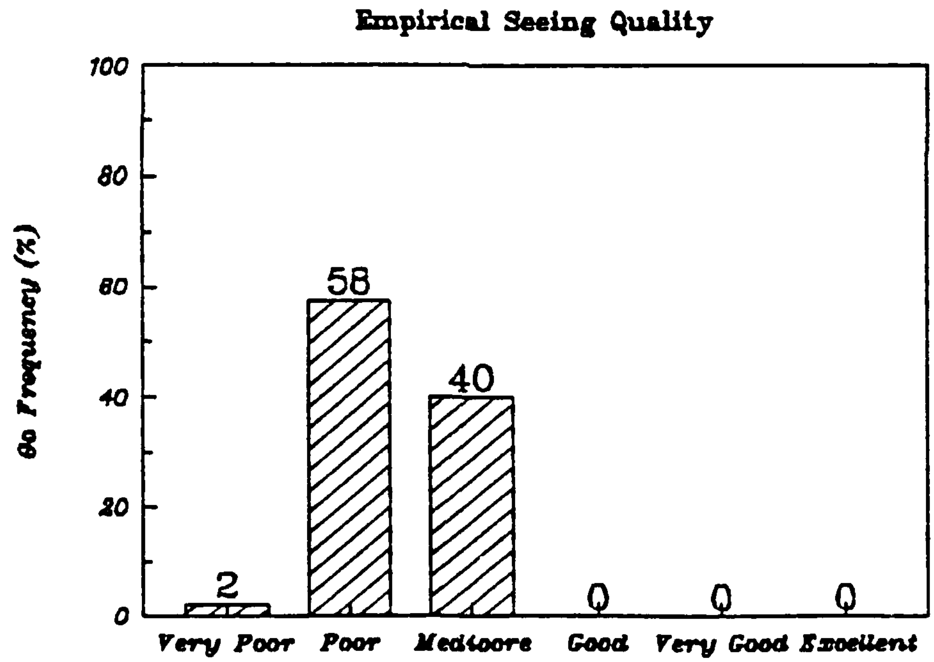
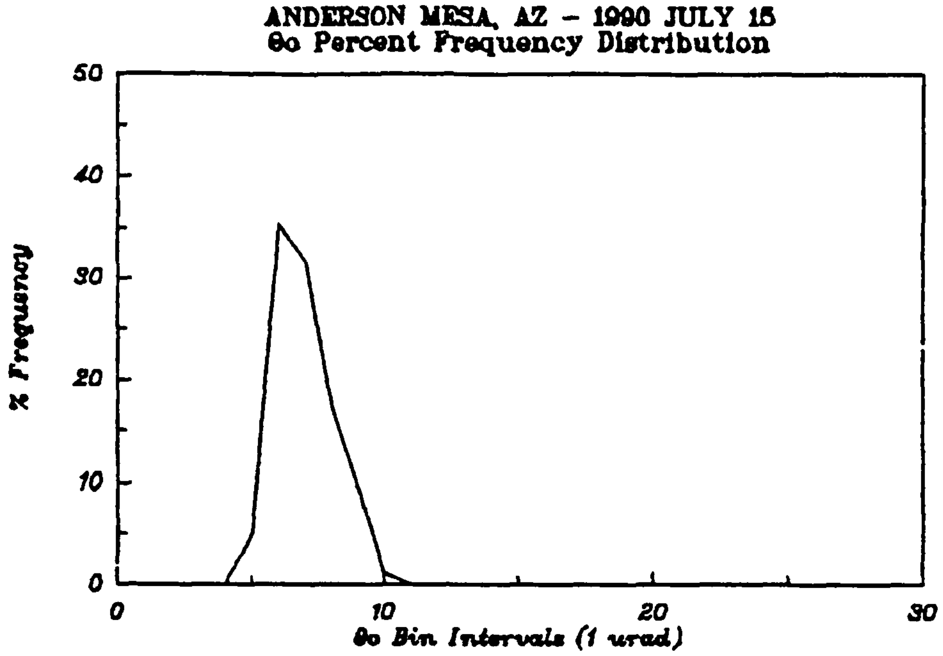


Fig 38. Anderson Mesa, Az θ_o Statistics: 1990 July 13



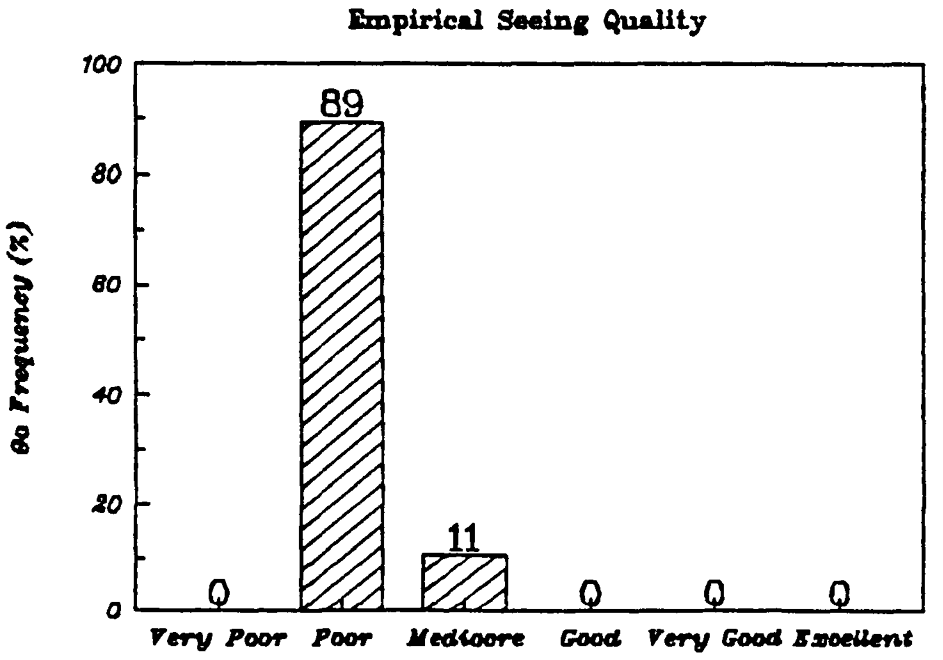
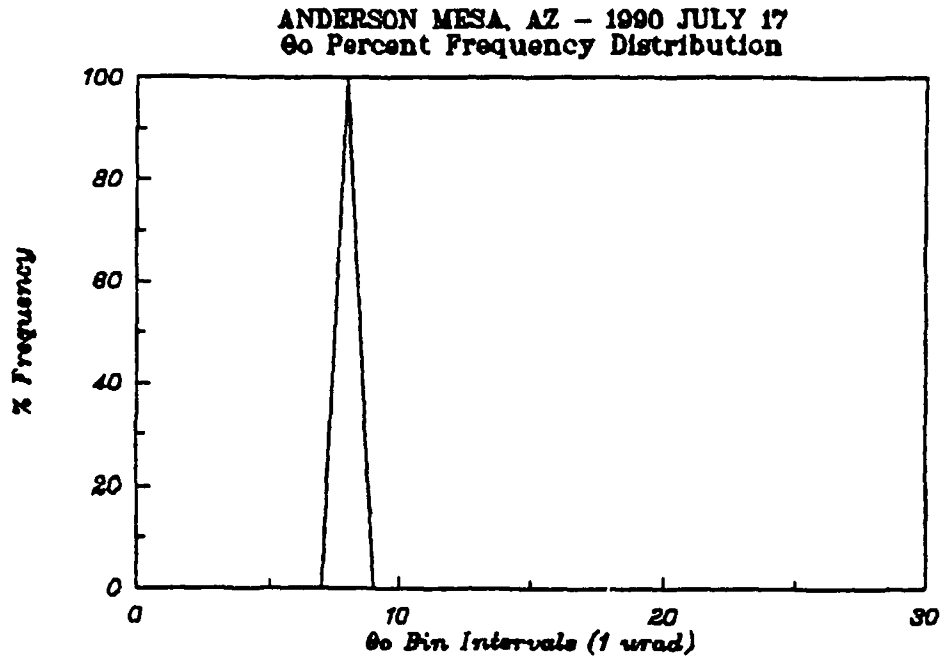


Fig 39. Anderson Mesa, Az Θ_o Statistics: 1990 July 15



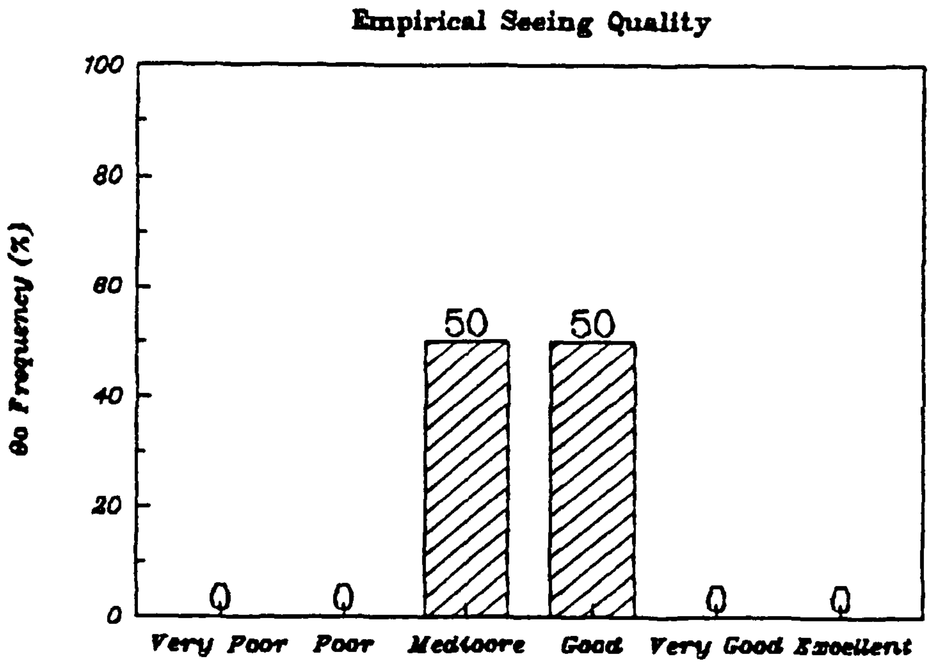
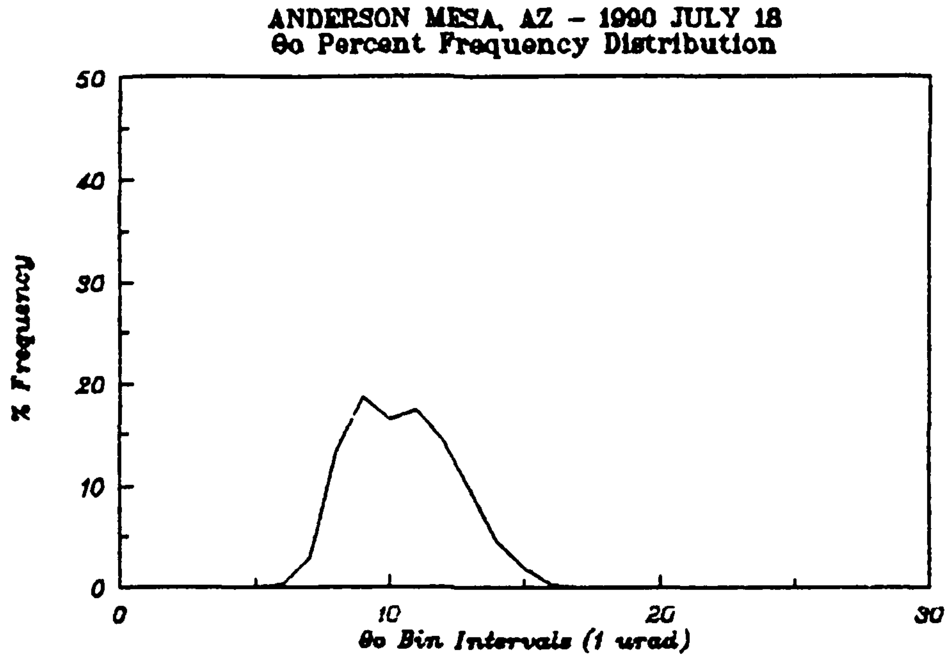


Fig 40. Anderson Mesa, Az θo Statistics: 1990 July 17



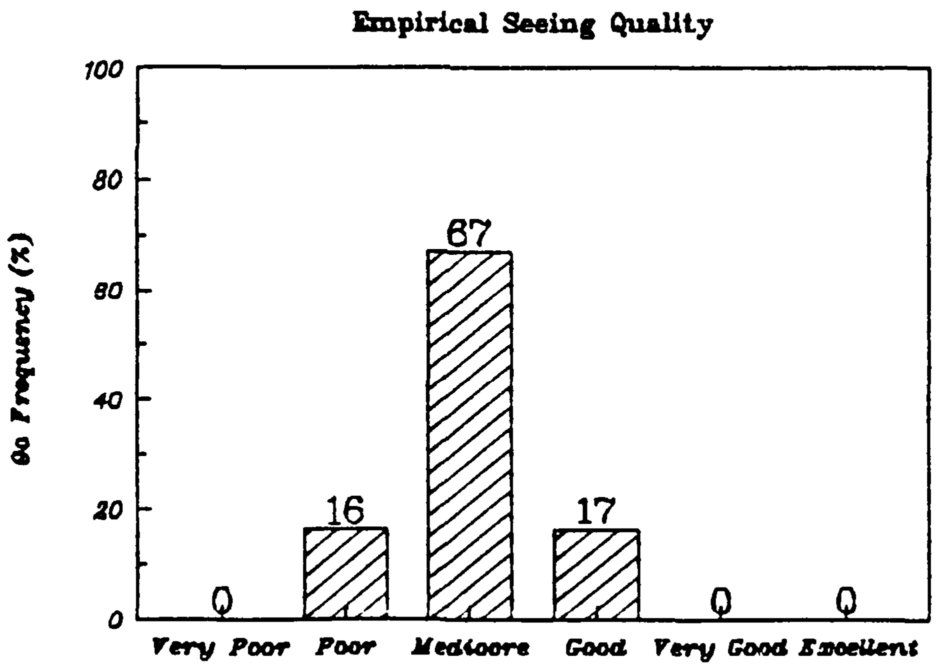
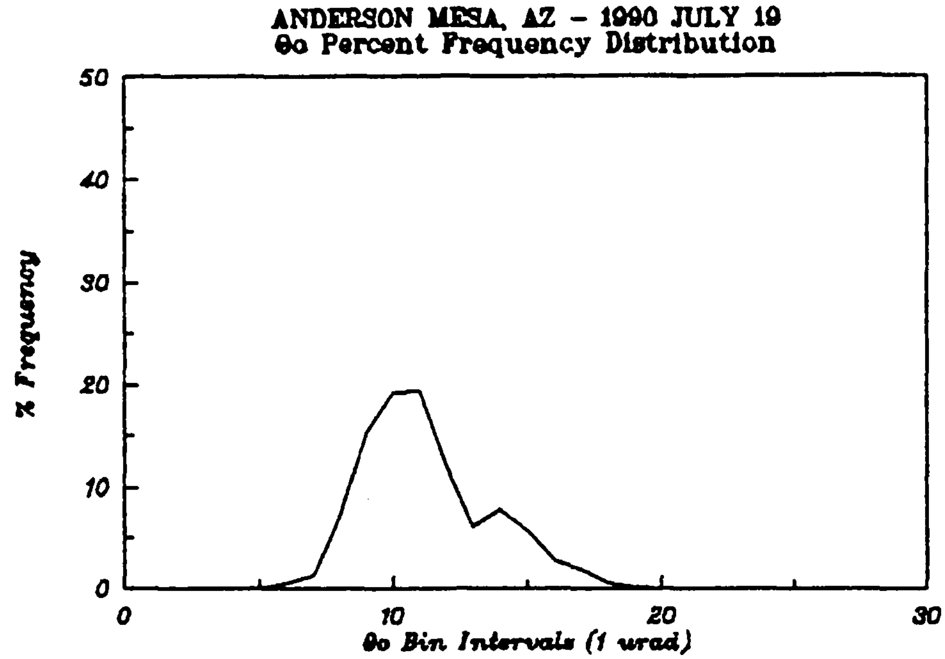


Fig 41. Anderson Mesa, Az θ_o Statistics: 1990 July 18



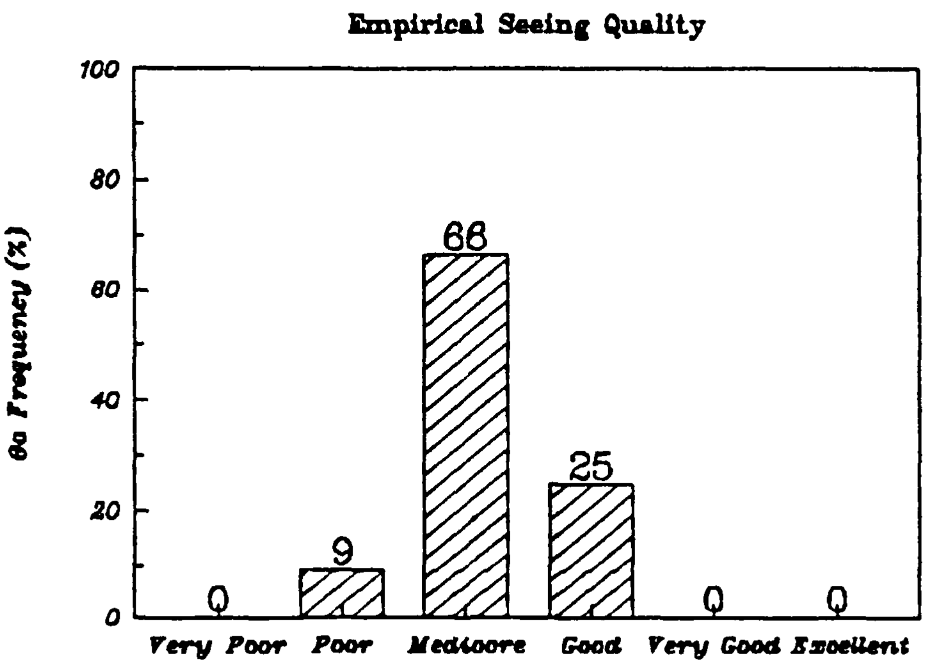


Fig 42. Anderson Mesa, Az θ_o Statistics: 1990 July 19

APPENDIX F. SEPT/NOV 1989, JULY 1990 r_o AND θ_o DISTRIBUTIONS

Appendix F presents the cumulative September 1989, November 1989, and July 1990 normalized frequency distribution for both r_o and θ_o . The measurements contained in these figures represent all the 17-28 September 1989, 13-19 November 1989 and 10-19 July 1990 processed NPS optical data taken at Anderson Mesa and the United States Naval Observatory near Flagstaff, Arizona. Specifically, Figure 43 displays the distribution generated from the 2,773 September, 2,103 November and 1,501 July r_o samples. The 34,003 θ_o samples shown in Figure 44 incorporate: 16,355 September, 14,194 November and 3,454 July individual angies.

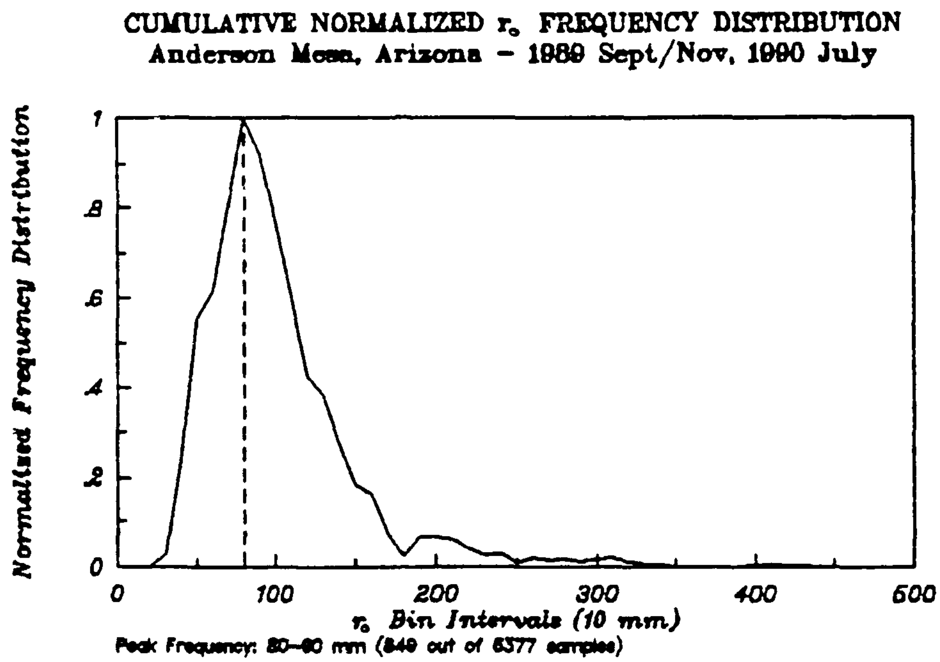


Fig 43. Cumulative r_o Distribution: 89 Sept/Nov, 90 July
The peak r_o bin interval is 80-90 mm.

CUMULATIVE NORMALIZED θ₀ FREQUENCY DISTRIBUTION
Anderson Mesa, Arizona – 1989 Sept/Nov, 1990 July

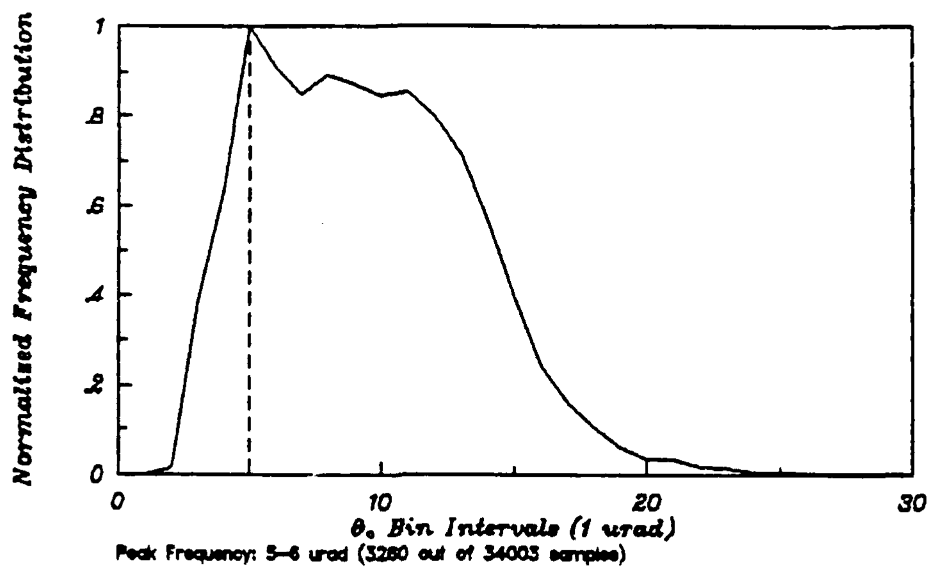


Fig 44. Cumulative θ_o Distribution: 89 Sept/Nov, 90 July
The peak θ_o bin interval is 5-6 urad.

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